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WATER & WASTEWATER ENGINEERING DIVISION

Outfall Sewershed Evaluation Study Plan
Project No. 1039

Model Development and Calibration Report – Final
Sanitary Sewer Overflow Consent Decree
Civil Action No. JFM-02-1524

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1. EXECUTIVE SUMMARY

The essential contents of this model development and calibration report (MDCR) are outlined in the Baltimore Sewer Evaluation Standards (BaSES manual) Section 7.8.1. Further, the MDCR is consistent with the Outfall Sewershed Model Development and Calibration Plan, submitted by the Joint Venture of Dewberry and Brown and Caldwell (the Joint Venture) to the City of Baltimore (City) on February 22, 2008 and subsequently approved by the City on June 5, 2008.

The MDCR contains a description of the model development; the main sections of the MDCR address the rainfall/flow monitoring, model development, and calibration results. The model conforms closely to the guidelines set forth in the BaSES manual; and any deviations from the procedures outlined in the BaSES manual are explained and justified. The model performance is demonstrated by comparing the simulated flows and water levels to measured values collected in selected dry and wet weather periods during the flow monitoring program. In summary, the quality of the model calibration demonstrates that the model is suitable to evaluate the hydraulic performance of the existing system and for investigating alternative improvements. Electronic files containing the model, additional documentation details, and calibration results will be submitted with the report on a compact disc.

1.1. Project Location/Description

The Outfall Sewershed consists of approximately 3.6 square miles of mixed residential development and industrial area located in the City of Baltimore. Baltimore County contains additional contributing area that is tributary to the Outfall and Outfall Relief Sewers between the City/County line and the Back River Wastewater Treatment Plant (WWTP). These contributing flows will be modeled by the Technical Program Manager.

The Outfall Sewershed is the most downstream sewershed that is tributary to the Back River WWTP. As such, all of the City's sewersheds in the Back River WWTP service area are tributary to the Outfall Sewershed. These include: Jones Falls, High Level, Low Level, Herring Run, and Dundalk Sewersheds. The Outfall Sewershed extends beyond the City/County line to the Back River WWTP. By contract, the hydraulic investigation and evaluation related to this MDCR is limited to the sewershed contained within the City of Baltimore.

Figure 1-1 shows the vicinity of the outfall sewershed and its geographic relationship with the tributary sewersheds.

Figure 1-1. Map of the Outfall Sewershed and Baltimore City Limits.

1.2. Consent Decree Requirements

On September 30, 2002, the City of Baltimore entered into a Consent Decree with the United States Environmental Protection Agency (EPA) and the State of Maryland Department of the Environment (MDE) to eliminate wet-weather sanitary sewer overflows. In August 2007, the City of Baltimore Department of Public Works (City) contracted the joint venture project team of Dewberry and Brown and Caldwell (the Joint Venture) to complete a comprehensive investigation and evaluation of the wastewater collection system in the Outfall Sewershed as required under Paragraph 9 of the Consent Decree.

Paragraph 12 of the Consent Decree defines the requirements of the collection and transmission system model. Consent Decree paragraph 12E requires a certification that the sewershed model includes the elements required in paragraphs 12A and B. This model development and calibration report is the substantive material upon which the certification required in paragraph 12E is based. The model is capable of and can be used for predicting the volume of wastewater flow, the hydraulic grade line (water levels) at any point in the modeled system, the capacity of the system, and the locations where overflows are likely. The model configuration is based on representative, accurate, and verified system attribute data. The model has been calibrated and validated with spatially and temporally representative rainfall and flow data collected during the flow monitoring program.

Modeling requirements per the Consent Decree are defined in even greater detail in the BaSES Manual, Section 7 (Hydraulic Modeling). The appropriate sections of the BaSES manual will be cited throughout this report to clearly identify how the development and calibration of the Outfall Sewershed model fulfills the requirement of the BaSES manual and the objectives of the Consent Decree.

1.3. Purpose and Scope

The purpose of this MDCR is to document the development and calibration of the Outfall Sewershed model. The report contains descriptions of the data sources used to develop and calibrate the InfoWorks™ model. The report also presents simulation results compared to measured values to demonstrate the quality of the model simulations. The results verify that model simulations produce an accurate representation of the flows generated in the Outfall Sewershed for dry and wet weather conditions. The results also verify that the model successfully routes flow through the sewer network to predict water levels, flow rates, and volumes.

The scope of this report addresses the data sources and the model development assumptions. A sufficient number and variety of results are presented in the body of the report to demonstrate the validity of the model. Additional results are available in the Appendix and in electronic form on the enclosed compact disc. The report is limited to the calibration and development of the Outfall Sewershed as defined by the Joint Venture contract. Upstream sewersheds are represented by measured inflow hydrographs that are assumed to be an accurate representation of the flows entering the Outfall Sewershed. As per the Joint Venture contract, no attempt has been made to verify the flows from the upstream sewersheds, nor has this calibration effort involved any collaborative interaction with the other sewershed consultants.

2. RAINFALL AND FLOW MONITORING

2.1. Rainfall and Flow Monitoring Program

The City recently completed a 1-year City-wide rainfall and flow monitoring program in accordance with Paragraph 9.E.-(iii) of the Consent Decree. The objective of the monitoring program was to collect data necessary to establish the relationship between rainfall and wastewater flow in the collection system.

The ground based network of rain gauges provides the fundamental data for rainfall evaluation. Radar rainfall estimates were developed in coordination with the ground based rain gauge data to increase the spatial resolution of the rainfall definition in the model. The radar rainfall data, also known as CALAMAR rainfall data, will be discussed below; however, it is important to note that the radar rainfall data is not an independent source of information distinct from the ground based rain gauge data. The rainfall intensities detected by the radar system are adjusted to correlate with the ground based rainfall data; therefore, the radar rainfall data is coupled with the ground based rain gauge data to produce the CALAMAR rainfall data used in the InfoWorks™ model.

The flow meter locations were identified by the City in coordination with the flow metering consultant. The program recorded flow meter data from May 9, 2006 to May 9, 2007. All of the flow monitoring data for the modeling effort is stored and accessed via the Sliicer.com software.

2.2. Rain Gauge and Flow Monitoring Sites

Figure 2-1 shows the locations of the ground based rain gauges in the City of Baltimore and Baltimore County. None of the gauge sites are located in the Outfall Sewershed. The four closest gauges are: JF12-RG to the West, HR15-RG to the Northeast, HR16-RG to the East, and DU04-RG to the South.

Figure 2-1. Rain Gauge Locations for the City of Baltimore.

The flow monitoring locations are shown in Figure 2-2 along with the associated flow meterbasin tributary areas. Figure 2-3 is a schematic of how the flow meters of the Outfall Sewershed are interrelated and includes some of the major wastewater conveyance features in and around the Outfall Sewershed. The flow meter names are used to identify the meterbasin (or incremental meter basin) area upstream of the meter sites.

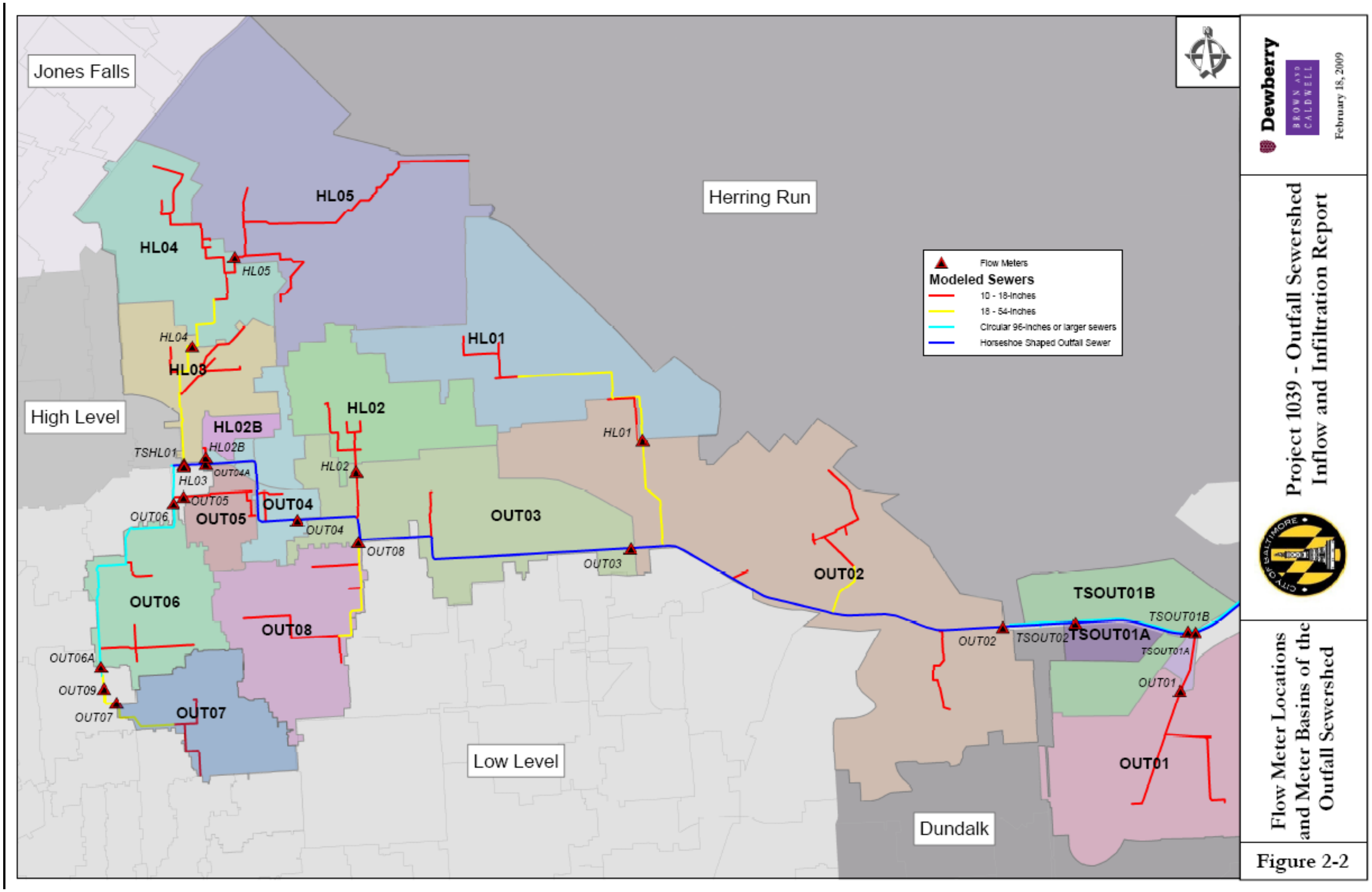


Figure 2-2. Flow Meter Locations and Meter Basins of the Outfall Sewershed

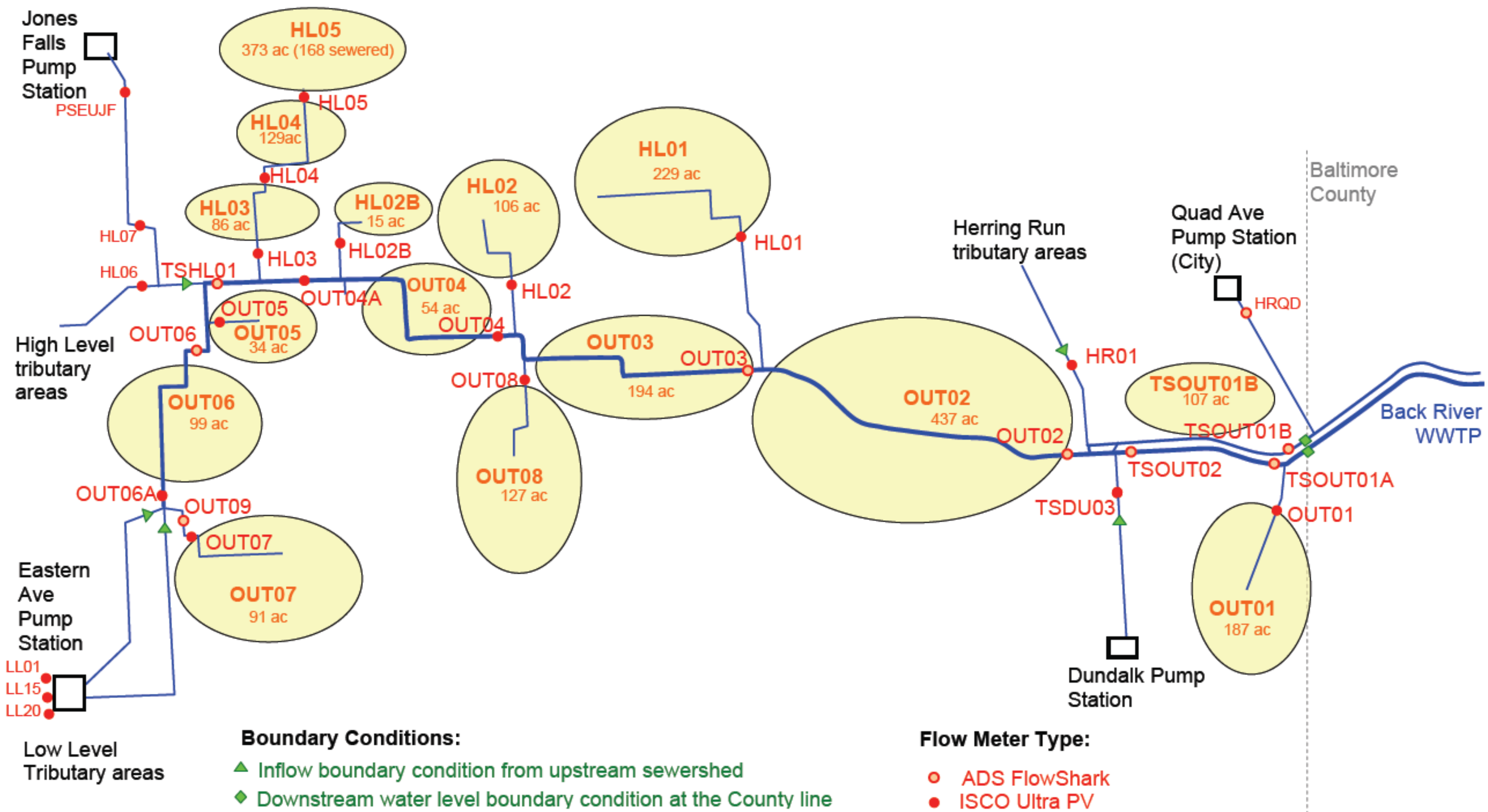


Figure 2-3. Schematic of Flow Meters and Meter Basins in the Outfall Sewershed

2.3. Discussion of Flow Monitoring Data

Flow monitoring sites located along the branches of the Outfall Sewershed collection system can be used to estimate the flows generated by the sewer service areas (SSAs) in those branches. Most of these branches have a single flow meter site located near the downstream end of the branch before joining the major trunk sewers. The branch containing meters HL03, HL04, and HL05 required evaluation using incremental flows for the incremental meter basin areas. The meter basin served by HL05 can be evaluated directly, but the meter basin served by HL04 must be evaluated by subtracting the measured flow values at HL05 from HL04. Likewise, the meter basin served by HL03 must be evaluated by subtracting the measured flow values at HL04 from HL03.

The flow monitoring sites located along the major trunk sewers (99-, 114-, 144- x 129-inch and 147- x 132-inch) are useful for evaluating the large scale hydraulic performance of the model, but are not useful for the specific determination of the tributary flows in the meter basin areas that are directly tributary to the trunk sewers. This is because the incremental flows from these relatively small tributary areas are insignificant relative to the total flows at the major trunk sewer meter sites. For example, based on population and employment data, the 54 acre tributary area between meters OUT04A and OUT04 likely generates an average dry weather flow of approximately 0.1 million gallons per day (mgd). The total flow at meter site OUT04 is approximately 75 mgd, and upstream at meter site OUT04A the total flow has essentially the same magnitude. Therefore, it is not possible to evaluate the incremental flow for the small 54-acre area between the two meters. Meters such as OUT04 and OUT04A are used to evaluate the large scale hydraulic performance of the model (such as water level), but are not used to calibrate the flow from subcatchments in the vicinity of the meters on the major trunk sewers.

Table 2-1 is a list of meter sites and how the data was used for the model development and calibration. A few of the smaller meters do not have data or the limited data is not useful for model development. The typical order of magnitude of the flow is given to demonstrate the dramatic difference in the magnitude of flows along the major trunk sewers compared to the smaller branch sewers.

Table 2-1. Flow Meters and Data Usage

Flow Meter Site	Used for meter basin calibration	Used for large scale hydraulic performance	Pipe Diameter (inches) Flow Meter Type	Typical Magnitude of Dry Weather Flow (mgd)	Comment
HL01	Basin HL01 220 acres		24” Isco	0.3	
HL02	Basin HL02 484 acres		15” Isco	0.5	
HL02A			8” Isco		Flows are very small and uncertain. Not used.
HL02B	Basin HL02B 15 acres		10” Isco	0.05	Flows are very small and uncertain.

Table 2-1. Flow Meters and Data Usage					
Flow Meter Site	**Used for meter basin calibration**	**Used for large scale hydraulic performance**	**Pipe Diameter (inches) Flow Meter Type**	**Typical Magnitude of Dry Weather Flow (mgd)**	**Comment**
					Not used
HL03	Incremental basin between HL03 and HL04 89 acres		24” Isco	0.8	
HL04	Incremental basin between HL04 and HL05 131 acres		22” Isco	0.5	
HL05	Basin HL05 168 acres		15” Isco	0.3	
OUT01	Basin OUT01 134 acres		18” ADS FlowShark	0.4	Limited meter data available after February 2007
OUT02		Outfall Sewer	147” x 132” ADS FlowShark	78	
OUT03		Outfall Sewer	147” x 132” ADS FlowShark	77	
OUT04		Outfall Sewer	144” x 129” Isco	75	Low bias in flow values.
OUT04A		Outfall Sewer	144” x 129” Isco	75	Low bias in flow values
TSHL01		Inflow Boundary Condition	144” x 129” ADS FlowShark	74	High Level and Jones Falls sewershed flows into the Outfall Sewershed model
OUT05	Basin OUT05 34 acres		15” Isco	0.2	Flows are very small and uncertain. Not used.
OUT06		Trunk Sewer from Low Level	99” ADS FlowShark	26	
OUT06A		Inflow Boundary Condition	99” Isco	26	Low Level sewershed flow into the Outfall Sewershed model
OUT07	Basin OUT07 82 acres		24” Isco	0.3	
OUT08	Basin OUT08 125 acres		24” Isco	0.5	
OUT09			30.5 ADS FlowShark	0.3	Monitors basin OUT07. Strongly influenced by Eastern Avenue Pump Station from Low Level
TSOUT02		Outfall Sewer	147” x 132” ADS FlowShark	67	.
TSOUT01A		Outfall Sewer Downstream Level Boundary Condition	147” x 132” ADS FlowShark	67	

Table 2-1. Flow Meters and Data Usage					
Flow Meter Site	**Used for meter basin calibration**	**Used for large scale hydraulic performance**	**Pipe Diameter (inches) Flow Meter Type**	**Typical Magnitude of Dry Weather Flow (mgd)**	**Comment**
TSOUT01B		Outfall Relief Sewer Downstream Level Boundary Condition	114" ADS FlowShark	33	
HR01		Inflow Boundary Condition		18	Herring Run sewershed flow into the Outfall Sewershed model
TSDU03		Inflow Boundary Condition		4	Dundalk sewershed flow into the Outfall Sewershed model

The flow metering contractor was required to collect useable flow data a minimum of 90% of the time throughout the nominal monitoring period.

In the event that depth measurements are available but velocity measurements are missing, the uptime requirement may be satisfied by inferring velocity from a reliable depth measurement. This type of circumstance would not be considered downtime if the flow metering contractor demonstrated that accurate data could be obtained without the velocity measurement, and that the loss of velocity data was not caused by maintenance neglect. The flow metering contractor was required to identify all inferred velocity data or other data derived from inferred data in all reports and deliverables. No data points in the Sliicer database for the Outfall sewershed have been identified as inferred; therefore, it is assumed that all of the velocity values are actual flow meter measurements.

The Outfall Sewershed Joint Venture screened the values in the Sliicer database to determine the percent of non-zero data values (for flow, depth, and velocity) in the actual sampling duration; these values are also listed in Table 2-2. The percentage of non-zero values is based on the actual sampling duration of each site, not on the nominal monitoring program duration. For example, for OUT01 the sampling duration was 90 days during which 100% of the values are non-zero.

The uptime and availability of non-zero data values for each flow meter in the Outfall Sewershed is listed in Table 2-2. The uptime information was prepared by the City's technical program manager.

Table 2-2. Flow Meter Uptime

				Percent of Sampling Duration with Non-zero Values			
Flow Meter	Start Sampling Date	End Sampling Date	Sampling Duration (days)	Non-zero Flow	Non-zero Depth	Non-zero Velocity	City Provided Uptime Percentage
HL01	5/9/2006	1/23/2007	259	90%	92%	91%	90.0%
HL02	5/9/2006	3/19/2007	314	86%	83%	86%	86.0%
HL02A	NO RELIABLE DATA AVAILABLE						
HL02B	5/9/2006	4/1/2007	327	61%	83%	80%	
HL03	5/9/2006	5/18/2007	374	100%	87%	87%	98.2%
HL04	5/9/2006	5/18/2007	374	100%	87%	87%	99.8%
HL05	5/9/2006	5/18/2007	374	99%	87%	87%	98.2%
OUT01	2/17/2007	5/18/2007	90	100%	100%	100%	100.0%
OUT02	5/9/2006	3/31/2008	692	99%	99%	99%	98.4%
OUT03	5/9/2006	5/18/2007	374	99%	99%	99%	98.4%

OUT04	5/9/2006	5/18/2007	374	95%	99%	95%	90.1%
OUT04A	5/9/2006	5/18/2007	374	99%	99%	99%	99.5%
OUT05	NO RELIABLE DATA AVAILABLE						TBD
OUT06	5/9/2006	3/31/2008	692	100%	100%	100%	98.9%
OUT06A	5/9/2006	5/18/2007	374	85%	98%	85%	78.4%
OUT07	5/9/2006	5/18/2007	374	87%	61%	50%	86.1%
OUT08	5/9/2006	5/18/2007	374	97%	96%	99%	95.6%
OUT09	8/17/2006	5/18/2007	274	98%	98%	98%	89.3%
TSHL01	5/9/2006	3/31/2008	692	97%	97%	97%	95.2%
TSOUT01A	5/9/2006	3/31/2008	692	99%	99%	99%	99.3%
TSOUT01B	5/9/2006	3/31/2008	692	100%	100%	100%	99.8%
TSOUT02	5/9/2006	2/28/2007	295	93%	93%	95%	73.5%

2.4. CALAMAR Rain Data

CALAMAR is a software and radar service package that integrates high resolution radar data with rainfall measurements collected from a ground based rain gauge network to produce accurate, dependable rainfall maps and rainfall hyetographs useful for hydrologic modeling. CALAMAR uses NEXRAD radar images from the National Weather Service along with ground based rain gauge data to transform the raw radar reflectivity images into geographically precise, local rainfall intensity hyetographs.

The radar rainfall estimates are assigned to a 1 kilometer by 1 kilometer grid of “pixels”; each pixel represents a virtual rain gauge location. Figure 2-4 is an overlay of the radar pixel grid on the InfoWorks^{TM} model network to show the size of the pixels relative to the subcatchment areas.

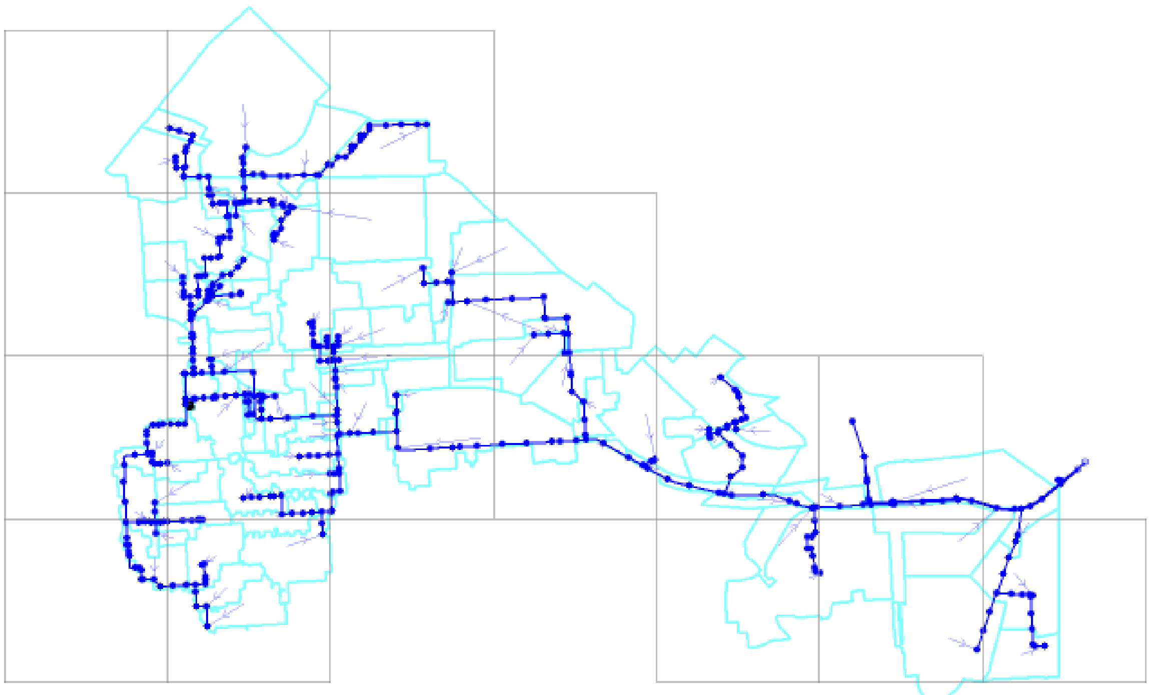


Figure 2-4. Radar Rainfall Pixel Grid Overlaid on InfoWorks™ Model Network.

2.5. Sliicer.com

Sliicer is a data storage and analysis tool developed by ADS Environmental Services. The web based tool stores data from the flow meters, rain gauges, and CALAMAR radar rainfall estimates. Sliicer uses a number of data processing tools to evaluate dry weather flow, wet weather flow, and the rainfall derived infiltration and inflow (RDII) characteristics that can be derived from the flow meter data. The Sliicer tool is not a wastewater flow model nor is it a hydraulic routing model; those modeling functions are in the InfoWorks™ software. The Sliicer tool is useful for viewing the data, reviewing the correspondence between rainfall and wastewater flow, and developing preliminary model parameters that will be utilized in the InfoWorks™ software. Therefore, the Sliicer database is the host for the measured data, but the InfoWorks™ model stores all simulation results.

3. MODEL DEVELOPMENT

3.1. General

In general, a hydraulic model contains three essential components:

- The network of sewer infrastructure (pipes, pumps and structures);
- Tributary basins served by the sewer network (i.e., the source of flows to the network), and

- Boundary conditions (i.e., flows and water levels that represent the system beyond the model boundaries).

The network, basins, and boundary conditions will be described in the following sections, after a brief discussion of datum references and the modeling software.

3.1.1. Horizontal and Vertical Datums

According to BaSES 7.4.2, the Maryland State Plane Coordinate System (NAD83-Feet) should be used for the horizontal datum. The vertical datum for the model is the North American Vertical Datum of 1988 (NAVD88).

3.1.2. InfoWorks™ CS

The Joint Venture team used the InfoWorks™ CS hydraulic modeling software (version 8.5) by Wallingford Software to build a hydraulic network model of the Outfall Sewershed. The InfoWorks™ model satisfies the requirements of Consent Decree paragraph 12B and is useful to perform a hydraulic evaluation of the sewer system in accordance with Paragraph 9.F of the Consent Decree.

Table 3-1 describes the information used to construct the InfoWorks™ model.

Table 3-1. Required Model Development Data

Category	Information	Needed	Needed, can be estimated	Not Needed, but helpful	BaSES Note	Data Source	Entity Relied Upon for Data
Manholes/ Nodes	Node ID	x				GIS	City
	Node Type (Manhole, break, outfall, storage)	x			At all manholes, pipe intersections, outfall, etc.	Manhole Inspections; GIS	City
	X Coordinate	x				Survey	
	Y Coordinate	x				Survey	
	Ground Level	x	x		Missing ground levels can be interpolated based on a digital terrain model.	GPS; Survey	
	Flood Level		x		Usually assumed to be same as ground level	Survey	
	Chamber Floor Level		x		Estimated assuming the lowest connecting pipe. Comparison should be made with records to verify.	As-Built Drawings; Manhole Inspections	City
Manholes/ Nodes	Chamber Plan Area		x		InfoWorks™ has functionality to estimate these; however, record or field inspection information is	Estimated by InfoWorks™	
	Chamber Roof Level		x			Manhole Inspections	

Table 3-1. Required Model Development Data							
Category	**Information**	**Needed**	**Needed, can be estimated**	**Not Needed, but helpful**	**BaSES Note**	**Data Source**	**Entity Relied Upon for Data**
	Shaft Plan Area		x		recommended for non-standard nodes (i.e. wet wells, storage tanks, etc.)	Estimated by InfoWorks™	
	Flood Type		x		Flood type and storage parameters are required, but are generally estimated from existing information.	InfoWorks™ Default; Manhole Inspections	
	Floodable Area		x				
	Flood Depth 1		x				
	Flood Area 1 (%)		x				
	Flood Depth 2		x				
	Flood Area 2 (%)		x				
	Locations where sanitary cross-connects with the storm system	x				Manhole Inspections; Dye & Smoke Tests	
	Locations of flooding complaints/capacity issues/other field notes	x			Required to determine modeled extents. Compare to predicted results for calibration.	WIC Complaints, List of Unpermitted SSOs	City
Pipes	Upstream Node ID	x				Manhole and CCTV inspections; GIS	City
	Downstream Node ID	x				GIS	City
	Length		x		Generally estimated from node XYs or GIS	GIS	City
	Shape ID	x			If the pipe is not circular, information on the exact shape is required. If not an InfoWorks™ standard shape, enough information to enter in the shape into InfoWorks™ is required.	As-Built Drawings	City
	Width	x				As-Built Drawings; Manhole and CCTV Inspections	City
	Height	x			If pipe is circular, the height by default will equal the width.	As-Built Drawings; Manhole and CCTV Inspections	City

Table 3-1. Required Model Development Data							
Category	**Information**	**Needed**	**Needed, can be estimated**	**Not Needed, but helpful**	**BaSES Note**	**Data Source**	**Entity Relied Upon for Data**
	Roughness Type	x	x - if pipe material known		Manning's roughness coefficients will be used. Value is generally based on material type. In the absence of pipe material data, a standard value of 0.013 should be used.		
	Bottom Roughness	x					City
	Top Roughness	x					City
	Sediment Depth			x	Pipe sediment depths can be accounted for in the model. If unknown sediment is present in the pipe, sediment depths can be estimated during model calibration (however other conditions in the physical system causing elevation observed water levels may be incorrectly attributed to sediment accumulation).	CCTV Inspections (If Available	City
	Upstream Invert Level	x				As-Built Drawings; Manhole Inspections	City
	Downstream Invert Level	x				As-Built Drawings; Manhole Inspections	City
	Pipe age/material/condition	x			Not required to run model, but needed for system analysis.	As-Built Drawings; CCTV Inspection	City

3.2. Sewer Infrastructure Network Development

Consent decree paragraph 9.F (i) gives general instructions for the model development, which are specified in greater detail in BaSES 7.4.1. The model network contains:

- All gravity lines that are 10-inches in diameter or larger
- All 8-inch sewer lines that convey or are necessary to accurately represent flow attributable to a service area in each of the collection system sewershed service areas
- All gravity sewer lines that convey wastewater from one pumping station service area to another pumping station service area
- All gravity sewer lines that have caused or contributed to, or that the City knows are likely to cause or contribute to capacity-related overflows
- All manholes, junctions, and structures along modeled sewer lines
- Simulated control structures (gates, weirs, pump stations) as they exist in the field

Within the Outfall Sewershed, there are no pump stations or other control structures. Furthermore, the network extent is adequately defined by the 10-inch pipes; therefore, no smaller pipes are represented in the model.

The configuration of the model is based on GIS data that is built on field surveyed data (supplemented by as-built drawings). This is to satisfy the Consent Decree paragraph 12.B-(ii)-(a) requirement that the system configuration be based on system attribute data that is representative, accurate and verified.

3.2.1. GIS Development

The Macro Model provided by the City was modified based on the existing GIS and field inspection data. The Macro Model contained pipes with diameters 18-inches and larger so the Joint Venture was responsible for appending the model network using the City's GIS database with sewers greater than or equal to 10-inches. The model network was then attributed with invert information obtained from manhole surveys and inspections. If survey or inspection data were not available, necessary attribute data was populated from existing GIS data or record drawings.

3.2.2. Exporting the GIS Data to InfoWorks™

The InfoWorks™ Data Import Centre was used to import GIS data updates to the model. GIS shapefiles were used as the file format for updated data, and the shapefile data fields were mapped to the respective InfoWorks™ data fields using the field mapping configuration settings in the Data Import Centre. GIS updates primarily consisted of conduit and node attribute updates (e.g., invert and ground elevations).

3.2.3. Manhole Inspection Data

Manhole inspections were conducted within the Outfall Sewershed per the standards described in Section 4 of the BaSES Manual. Manholes were inspected in order to provide attribute and condition assessment information for all accessible structures within the sewershed. Additionally, manhole inspections served as an I/I source detection method. A typical manhole inspection collected asset attribute and condition data, connecting pipe information (diameter, depth from rim, and seal condition), as well as any evidence of I/I or current/previous surcharging. Manhole inspection crews collected pipe diameter and invert measurements utilizing a Pipe Mic fixed to a standard survey rod. A rod level was used to assist the crews in collecting the best measurement data possible. Pipe invert depth measurements were then used in conjunction with manhole rim surveys to determine the modeled pipe invert elevation. For the purpose of the model calibration, pipe inverts were collected from record drawings for any inaccessible manholes inverts.

3.2.4. Record Drawings

The City provided the Joint Venture with available record drawings for manholes and sewers within the Outfall Sewershed. Record drawings were primarily used to resolve issues and conflicting information between the GIS and field inspection data. In some instances, record drawings provided the only source of pipe invert data due to the inability to access a manhole or difficulty encountered while measuring the pipe invert. Specifically, the large diameter (96-inches and greater) sewer inverts within the Outfall Sewershed could not be measured by inspection crews due to the manhole's placement along the side of each pipe making the invert inaccessible, high flow volumes creating difficulty in obtaining accurate measurements, and significant sediment depths providing false measurements. However, most of these inverts were measured by survey crews from Dewberry. A methodology was developed to determine these inverts whereby measurements were taken to the crown of the conduit and adjusted to the invert of the conduit in accordance with detailed sections of the Outfall and Outfall Relief Sewers as shown on the Contract Drawings. These inverts have been used to verify the converted as-built drawing inverts which were used in the model. This was decided due to the amount of deterioration in the crown of the Outfall sewer which could affect the accuracy of the data obtained.

Many of the Outfall Sewershed record drawings dated from the early 20th century and therefore required datum conversion prior to loading into the model. These datum conversion factors are based on the datum used (Baltimore City Metropolitan District (BCMD), NGVD 29 or NAVD 88) for preparation of the original contract drawings.

3.2.5. Surveys

The Joint Venture obtained x, y, and z coordinates of all accessible manholes (both modeled and non-modeled) necessary in the development of the hydraulic model per the requirements outlined in Section 4 of the BaSES Manual.

The manholes were surveyed by GPS methods where directly accessible with Trimble R8 GNSS/ VRS equipment. This high quality unit allows for accuracies of +/- 10mm + 1ppm RMS for horizontal measurements, and +/- 20mm + 1ppm RMS for vertical measurements.

In areas where a total station was used to establish manhole locations due to multipath or other obstructions to satellite observations, we used Topcon GPT 3000 LW geodetic total stations. These instruments have an EDM (distance) accuracy of +/- 3 mm +2ppm an angular accuracy of 2 arc seconds.

In accordance with the BaSES requirement, the survey datum was based on NAD83 (North American Datum 1983) for horizontal measurements and NAVD88 (North American Vertical Datum 1988) for vertical measurements

Due to the presence of significant sediment in the large diameter (greater than 96-inches) pipelines in the Outfall Sewershed, a sonar inspection was conducted below the wastewater flow line to determine the volume and depth of the sediment. Sediment profiles were collected and average depths were input into the model for each pipeline segment.

3.2.6. Data Flagging and User Text Fields

The data flagging system is used to identify the source of data used for model input. As the InfoWorks™ CS model of the Outfall Sewershed was populated with updated and revised data, The Joint Venture assigned flags to each dataset to indicate the source of the data. These data flags are consistent with the City's standard set of data flags. New data flags have been created as needed (new data flags are forwarded to the City's Technical Program Manager upon creation so that they can be added to the global data flag file and distributed to the other Sewershed Consultants for consistency.). Table 3-3 is a summary of the data flag codes.

Table 3-3 Summary of Data Flag Codes

Flag	Source
#A	"Asset Data"
#D	"System Default"
#G	"Data from GeoPlan"
#I	"Model Import"
#V	"CSV Import"
AD	"Assigned values by modeler"
AS	"inferred or assumed"
DS	"Import from Dewberry GIS" (added by the Joint Venture)
DV	"Default IWCS value - applied during initial import of geo-db"
FS	"Field Survey" (added by the Joint Venture)
GD	"Dump of City's geodatabase dated 11-13-2006"
HR	"Existing Herring Run Model developed by URS - Subtracted 1.52 feet from inverts."
IN	"Inferred/Interpolated Value"
RI	"Record Information"
WA	"Wastewater Analyzer's Office Model"

3.2.7. QA/QC Procedures for the Network

After the model development is completed and before flow calibration or simulations can be performed, the model network will be validated. The validation process will identify errors such as network discontinuity or conflicting asset data (network validation), as well as determine whether the model is accurately reflecting the sewer network (engineering validation).

Network Validation

After its development, but prior to running simulations, InfoWorks™ validates a model to confirm that it includes the minimum amount of information needed to complete a flow simulation. This validation includes checking for network continuity and parameters outside of the reasonable range, as well as identifying missing information, such as invert elevations, pipe size, pipe slope, etc. From this validation, InfoWorks™ will output a list of errors and warnings. Any errors must be fixed or the simulation will not work; any warnings may be addressed at the discretion of the user.

Engineering Validation

Engineering validation includes a custom validation of the network data. The auto-screening tool in the InfoWorks™ model was not used because of the iterative nature of the task. Instead, the Joint Venture performed a series of checks on the network by reviewing long section profiles and testing the model during simulation trials. The process was an iterative approach of reconciling the GIS data, field survey data, and record drawing. Using this information in conjunction with model calibration comparisons for flow the most likely model configuration was determined. Examples of common engineering validation data checks identified in the BaSES manual are:

- Upstream invert elevations of the pipes are higher than the downstream invert elevations;
- Pipes immediately upstream have the same or smaller diameter;
- Manhole rim elevations are greater than the highest invert elevation for pipes connected to the manhole and are generally at least five feet higher than the lowest outgoing pipe.

Other more involved validations involve checking sags in a long section profile, correlating sediment depth measurements to flow meter depth/velocity measurements, and balancing the flow between the Relief Sewer and the Outfall Sewer at the County line.

3.3. *Tributary Basin Development*

3.3.1. General

BaSES Manual Section 7.4.4 describes the model basin representation. The Outfall Sewershed area has been divided into subcatchments in which the sanitary wastewater flow is generated by users connected to the sewer system. In addition the sanitary flow, infiltration and inflow (I/I) also contribute to the total flow conveyed by the collection system. The model defines the sanitary flow (with a diurnal pattern) and the I/I response to wet weather using parameters in the model subcatchments.

For calibration purposes, the flow in the network is compared to the measured flows at the flow meter sites. The tributary area upstream of each flow meter site defines a meter basin; however, each meter basin is composed of a group of subcatchment areas. As a result, subcatchments inherit model parameters from the meter basin to which they belong.

3.3.2. Sewershed Service Areas and Model Subcatchments

Sewer service areas (SSAs) were initially defined by the City, but later refined into subcatchments to meet the requirements of the consent decree. The subcatchments are essentially the same as the sewer service areas (SSAs); however, some of the SSAs have been further subdivided to accommodate the need to load flow to each branch of network. SSAs were also divided due to the locations of the flow meters.

Figure 3-1 shows the subcatchments that are within the Outfall Sewershed, including the refinements the Joint Venture performed to reflect changes in the drainage patterns within the Outfall Sewershed based on the extended sewer network defined in the model. These changes follow the guidelines from Section 7.4.4 of the BaSES Manual.

A load point (a location in the hydraulic model where the flow enters the collection system) will be identified for each subcatchment in the model. These load points include all upstream nodes in the model, avoiding the occurrence of “dry pipes” (pipes that do not receive flow from an upstream load point). The JV project team identified the appropriate load point for each subcatchment.

For calibration, the subcatchments will be grouped according to the flow meter to which they are tributary. In general, all subcatchments within a flow meter basin have the same calibration parameters.

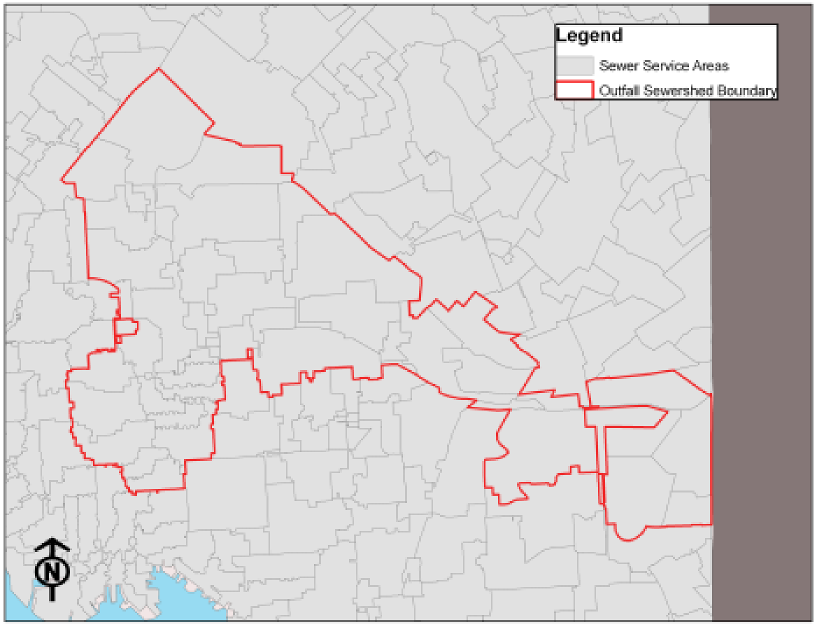


Figure 3-1. Sewer Service Areas for the Outfall Sewershed.

3.3.3. Dry-Weather Flow Development

3.3.3.1. General

Dry weather flow is discussed in the BaSES Manual Sections 3.2.3, 3.5 and 7.4.5. The objective of the dry weather flow development is to characterize the dry weather flow pattern so that during wet weather conditions it is possible to distinguish between flow due to infiltration and inflow (I/I) and the base sanitary flow. Calibration objectives focus on properly simulating the volume, diurnal peaks, and the timing of the diurnal pattern during dry weather conditions. Water consumption patterns and groundwater infiltration vary over time; much of the variability is periodic and repeated. The model development aims to represent the typical quantity and variability of dry weather flow by a fixed set of parameters. The model can not duplicate all of the flow patterns or periods of irregular flow; instead it is an approximate match to the dominant dry weather flow characteristics.

3.3.3.2. Flow Analysis

Base sanitary flows (BSF) have been developed by the City's Technical Program Management Team for each SSA (as described in the BaSES manual section 7.4.5). The BSF values represent the sanitary flow generated by users. The Project 1015 group tabulated BSF values for current (2007) and future projected population and land use conditions from 2000 to 2035, every 5 years. The BSF for the model subcatchments are based on the current 2007 BSF values for the SSAs using sewered area as a scaling factor.

The average dry day flow (ADF) from each SSA is the sum of the BSF and any groundwater infiltration (GWI).

ADF = BSF + GWI

The ADF is estimated from the flow meter data stored in Sliicer. The GWI is estimated as a calibration parameter to achieve a good match between the simulated flows and the measured flows during dry weather. The estimated GWI determined for each meter basin is assigned to the tributary subcatchments in proportion to area. In the InfoWorks^{TM} model, the GWI is input as a "trade flow" for each model subcatchment.

The typical diurnal pattern of each flow meter is also derived from the data in Sliicer. These patterns are stored in the InfoWorks^{TM} program as "domestic waste water profiles" for the BSF and "trade waste profiles" for the GWI.

3.3.4. Wet-Weather Flow Development

3.3.4.1. General

BaSES manual section 7.4.6 defines the modeling approach used to simulate the wet weather flow. This modeling approach assumes a direct relationship between rainfall and the wet weather flow response in the sewer system. The details of this deterministic relationship are described below; however, it is important to note that the modeling approach does not account for variable antecedent soil moisture conditions. The model calibration assumes that the hydrologic conditions experienced during the monitoring period are representative of typical hydrologic conditions. Special hydrologic conditions may not be properly modeled using this methodology (such as, events with significant snow melt, back to back events with a prolonged series of significant storms, or extreme events such as hurricane related storms).

The development of the model is based on rainfall and flow meter data. Uncertainties in both the rainfall and flow meter measurements are compounded in the process of developing a model relationship between the two. The uncertainties are not just due to the accuracies of the instruments, but also to the intrinsic variability of the quantities being measured. For example, rainfall measured at a gauge may or may not be a sufficient representation of the rainfall over the meter basin to which it is assigned. The rainfall and flow are measured at spatially separate locations. Overall, the correlation can be derived from the data by calibrating the model to many events. The objective of the calibration is to choose model parameters that realistically characterize the basin response to rainfall for the most probable conditions, even though the match may not be ideal for each and every event in the measurement record. The use of radar rainfall estimates seeks to improve the correlation between rainfall patterns and flow meter response, but rainfall is just one of many sources of variability.

3.3.4.2. SWMM Routine within InfoWorks™ CS

Rainfall derived infiltration and inflow (RDII) is simulated using the SWMM RUNOFF routines in InfoWorks™.

The following parameters are needed for each subcatchment in the model to develop wet-weather flows:

- Area
- R-Value
- Depression Storage
- Width
- Slope
- Overland Flow Routing Coefficients

Area

The **Contributing Area** parameter represents the area of each subcatchment, in acres, that is served by the collection system. The contributing area for each subcatchment will be calculated using GIS. Areas that are not sewered (i.e. cemeteries, golf courses, parks, etc.) will be deducted from the total area of subcatchments using GIS to determine the contributing area.

R-Value

The R-Value represents the fraction of the rainfall that enters the sewer system. Sliicer provides an initial estimate of the R-Value for each flow meter basin by plotting the RDII volume versus the rainfall depth (Q vs. I plot) and then developing the best-fit linear regression line and corresponding equation for the line (slope is the R-Value). In the InfoWorks™ model, the R-Value is input as the **Fixed Runoff Coefficient**. Once in the model, this coefficient may be adjusted to calibrate the model to wet-weather flows, providing a more accurate prediction of flow volume.

The equation for I/I volume using the R-value is:

V = K R A (D-DS)

Where V = Volume of I/I

K = a unit conversion constant = 1 MG/36.8 acre inches

R = dimensionless ratio of RDII volume to rainfall volume

A = metershed area (acres)

D = rainfall depth (inches)

DS = depression storage (otherwise known as initial rainfall abstraction) (inches)

Depression Storage

Depression storage represents the amount of rainfall (inches) that is lost to surface wetting, ponding, interception, and evaporation during a storm; this parameter is also commonly known as the "initial abstraction". Depression storage is estimated by the location where the linear regression line intercepts the x-axis of the Sliicer software's Q versus I Plot. Typical values range from 0 to 0.5 inches, but can vary greatly for the same area depending on the antecedent moisture conditions. The depression storage value will be entered into the appropriate Runoff Surface under the **Initial Loss Value** field of the InfoWorks™ model.

Width
The subcatchment width, known as the **Dimension** value in InfoWorks™, is a key calibration parameter that has no correlation to the actual dimensions of the subcatchment. During calibration, the subcatchment width value is adjusted so that the magnitude and time-to-peak of the simulated flows matches the observed peak flow in the monitoring data (peak RDII flow) for several storm events. Subcatchment width can greatly alter the shape of the hydrograph without impacting the volume. Because the width is directly proportional to the peak flow rate, its value may be adjusted as necessary to match the observed peak flows.

Slope
The **Slope** value represents the physical slope of the ground surface for combined sewer and storm water models in SWMM; however, because the SWMM model is being used to simulate RDII, this parameter is no longer physically-based. **Slope** is a not a sensitive calibration parameter.

Overland Flow Routing Coefficient
The **Overland Flow Routing Coefficient** is also known as the Manning's Roughness Coefficient (n) and is a secondary parameter that can be used to alter the shape of the hydrograph. A nominal value of 0.013 was used in the model for all subcatchments; however, this is not a sensitive parameter.

3.4. Boundary Condition Developments

The model is limited to the Outfall Sewershed itself; boundary conditions describe the relationship between the Outfall Sewershed and the other sewersheds (both upstream and downstream) that are beyond the extent of the Outfall Sewershed model. Upstream boundary conditions are the inflow hydrographs from the tributary sewersheds (High Level, Low Level, Herring Run, and Dundalk). The downstream boundary conditions are the water levels in the Outfall Sewer and the Outfall Relief Sewer at the Baltimore City/County line.

For the purpose of calibration, these boundary conditions are based on measured flow meter data at these boundary condition locations. Table 3-4 defines the boundary conditions in greater detail. For several of the boundary conditions, the approach had to be modified to accommodate the needs of the model and the nature of the monitoring data. The most significant exception relates to the need to use TSOUT01A level data for boundary conditions on both the Outfall Sewer and the Relief Outfall Sewer. If the actual measurements of TSOUT01B had been used for the Relief Sewer boundary condition, an unrealistically high flow would be conveyed by the Relief Sewer.

Table 3-4. Boundary Conditions			
Boundary Condition	**Type**	**Nominal data source Flow meter name**	**Modified data source**
High Level and Jones Falls Sewersheds	Upstream inflow hydrograph	TSHL01	Because the location of meter TSHL01 includes flow from Low Level, the boundary condition hydrograph was created by subtraction: (TSHL01 – OUT06)
Low Level Sewershed	Upstream inflow hydrograph	OUT06A	Bias in flow meter OUT06A produces low flow rate values. Data from meter OUT06 used instead.
Herring Run Sewershed	Upstream inflow hydrograph	HR01	No modification
Dundalk Sewershed	Upstream inflow hydrograph	TSDU03	No modification
Outfall Sewer at County Line	Downstream water level	TSOUT01A	Measured water level changes over time with diurnal variations and wet weather events. Removed outliers and data gaps from the measured data to create a smooth, realistic water level pattern.
Outfall Relief Sewer at County Line	Downstream water level	TSOUT01B	Level data from TSOUT01A was used instead of TSOUT01B. A small bias of lower water level values in meter TSOUT01B creates a hydraulic gradient that draws unrealistically large flows to the Relief Sewer from the Outfall Sewer; therefore, used TSOUT01A instead.

4. MODEL CALIBRATION

4.1. General

BaSES manual Section 7.5 defines the objectives and criteria to be used for the calibration of the dry and wet weather flows. The calibration compares the simulated flows and water levels in the InfoWorks™ model to the measured flows and levels at the monitoring sites.

The simulation results can be compared to the measured values using two types of plots. The first type of comparison contains time series plots of measured and simulated values (these are called "Observed and Predicted Reports" in the InfoWorks™ software. The other type is a statistical comparison plot of the measured versus the simulated values (such as measured event volume versus simulated volume, or measured peak flow vs. simulated peak flow). A best-fit linear regression line is used to evaluate the correlation between the two sets of values.

The calibration is evaluated for dry and wet weather conditions. The quality of the calibration is evaluated at the flow meter sites, but the model parameters are adjusted on the subcatchment level. Thus the calibration process involves iteration between the definition of subcatchment parameters and the evaluation of the outcome at the meter locations.

The subcatchments along the branch sewers in the Outfall Sewershed are calibrated using the meters located on the branch sewers. The remaining SSAs tributary to the major trunk sewers used nominal parameters to generate dry and wet weather flows. Meters located on the major trunk sewers are used to calibrate the large scale hydraulic properties and responses of the model (such as roughness, sediment, boundary conditions, and water depth). Thus there are two distinct applications of flow meter data to the model calibration; the smaller branch meters are used to calibrate the SSA flow generation parameters and the larger trunk meters are used to calibrate the large scale hydraulic parameters.

4.2. Dry-Weather Calibration

BASES manual Section 7.5.1 describes how the dry weather calibration depends on the appropriate values for groundwater infiltration (GWI) values. These values are initially defined by the evaluation of the measured flows in Sliicer. The calibration process is refined to match the InfoWorks™ simulation to the flow meter data.

4.2.1. Calibration Criteria – Dry Weather

The dry weather calibration criteria from the BaSES manual Section 7.5 are summarized in Table 4-1. For a representative dry weather period, the simulated volume of flow should be within -10% to +20% of the measured flow and the peak dry weather flow rate should be within -10% to +20% of the measured flow. The timing of the peaks of the diurnal pattern should be within 1 hour of the measured peaks. Subjectively, the general shape of the diurnal pattern should be representative for most of the dry weather conditions.

Table 4-1. Dry Weather Validation Criteria

Simulated response	Percent difference from observed measurements
Volume of Dry Weather Flow (assume a typical week duration)	-10% to +20%
Peak Dry Weather Flow Rate	_-10% to +20%
Timing of Peaks of Diurnal Pattern	Within 1 hour

4.2.2. Comparison of Metered and Modeled Results

The branch sewer meters were used to calibrate the SSAs; for these meters the dry weather comparison of the simulated results to the measured values is given in Table 4-2.

Five dry weather periods (representing a sum of 114 days of dry weather flow) were used to develop the dry weather calibration parameters. The values presented in Table 4-2 summarize the results for a 7-day validation period from 12/4/2006 to 12/11/2006 (except for two meter sites that use other periods as is explained further below). The calibration results are given for peak dry weather flow and the volume of dry weather flow. In most cases the results satisfy the calibration criteria given in Table 4-1; exceptions are explained below.

Table 4-2. Dry Weather Calibration

Branch Sewer Meters Used to Calibrate Sewer Service Areas

Meter	Peak Flow Measured (MGD)	Peak Flow Simulated (MGD)	Peak Flow Difference (MGD)	Peak Flow Percent Difference	Volume Measured (MG)	Volume Simulated (MG)	Volume Percent Difference
HL01	0.43	0.36	-0.07	-16%	1.86	1.94	5%
HL02	0.67	0.64	-0.03	-4%	3.56	3.78	6%
HL03	0.80	0.89	0.08	10%	4.42	5.24	19%
HL04	0.64	0.60	-0.04	-6%	3.32	3.40	2%
HL05	0.40	0.39	-0.01	-2%	6.78	6.81	0%
OUT01	0.53	0.53	0.00	-3%	5.77	6.04	5%
OUT05	No data	0.19			No data	1.18	
OUT07	0.33	0.38	0.04	13%	1.29	1.82	41%
OUT08	0.62	0.60	-0.02	-4%	3.26	3.36	3%
OUT09	0.55	0.39	-0.16	-28%	1.87	1.82	-2%

Meter HL01 has a unique flow pattern with a strong weekly cycle that does not conform simply to a typical weekday/weekend pattern. Because of this, it is difficult to represent this pattern in the InfoWorks™ model. The selected calibration is a reasonable compromise to adapt the model diurnal flow pattern to the measured flow pattern. Furthermore, the flow meter values for velocity were unusually high for a pipe of this size and slope. The measured depth data was reasonable and showed no evidence of surcharging. Therefore, the measured flow and volume values in the Table 4-2 are based on the depth data that was used to estimate flow rate values using Manning's equation. The simulated volume is within 5% of the measured volume. The simulated peak flow is 16% less than the measured peak flows; the absolute difference is within 0.07 MGD.

Meters HL02, HL03, HL04 and HL05 are calibrated within the criteria for dry weather flow. Meter HL05 was calibrated using data from August 2006 because the DWF during this period was higher than the DWF during the December 2006 period that was used for the other meters.

Limited data was available for OUT01 beginning in February 2007; the results in the Table 4-2 are based on a dry weather period from 4/25/2007 to 5/10/2007.

No valid flow meter data is available for OUT05; the SSAs tributary to this meter basin have been assigned nominal parameters to estimate the flow. Base sanitary flow (BSF) values were provided by the City for the SSAs. The sum of the BSF values is 0.084 MGD for OUT05. The simulated average dry weather flow is 0.17 MGD, which is twice the BSF rate.

Meters OUT07 and OUT09 monitor the same area; OUT09 is a FlowShark meter located a few blocks downstream of OUT07 which is an Isco meter. The flow at these meter sites can be influenced by high water levels in the 99-inch Sewer that is downstream of this branch. The flow and water level in the 99-inch Sewer are largely controlled by the operations of the Eastern Avenue Pump Station. The flow meter data at OUT07 and OUT09 show the influence of the operations of the pump station. The peak flow rate and volume at OUT07 and OUT09 should in principle be the same; the average dry weather flow is approximately 0.26 MGD. The variability in the measured data introduces large uncertainties in the measured values. In general, it appears that OUT07 yields a better estimate of the peak flow rate from this meter basin, while the peak flow rate recorded in OUT09 is higher due to the influence of cyclical backwatering due to pump operations in the 99-inch Sewer. Looking at measured volume values, it appears that OUT09 yields a more consistent estimate of the volume of flow. The calibration results do not conform to the calibration criteria because of the uncertainty in the measured data. The simulated flows are a reasonable representation of the flow from this meter basin.

Table 4-3 contains the dry weather calibration results for meters located on the major trunk sewers. (Like Table 4-2, these values are based on the 7-day period starting on 12/4/2006.) These meters were used to calibrate the overall hydraulic response of the sewer network. The simulation results at meters along the major trunk sewers are highly sensitive to the assumed boundary condition values. Gaps or irregularities in the measured data used for the boundary condition propagate through the model. For example, brief gaps in flow data at TSHL01 show up as abrupt drops in the simulated flow all along the Outfall Sewer. The dry weather calibration is based on a period of time with consistent boundary condition flows, but a few of the wet weather calibration events show are influenced by these gaps in the flow data used for boundary conditions.

The primary conclusion from this comparison is that the model is properly routing the input flow boundary conditions from the upstream sewersheds (that is, the measured flows from High Level, Jones Falls, Low Level, Herring Run, and Dundalk). The secondary benefit of this comparison is observations about the hydraulic consistency of the measured flow data. Most of the meters used in the large trunk sewers are FlowShark area-velocity meters; three of the meters are Isco area-velocity. In general, the FlowShark meters are better able to monitor the velocity in large pipes than the Isco meters (which are well suited to monitor flow in smaller pipes). Specific observations are noted below (progressing from the upstream to the downstream end).

Table 4-3. Dry Weather Calibration Major Trunk Sewer Meters Used to Evaluate Overall System Hydraulics (meters ordered from upstream to downstream)							
	Peak Flow				Volume		
Meter	Measured (MGD)	Simulated (MGD)	Difference (MGD)	Percent Difference	Measured (MG)	Simulated (MG)	Percent Difference
OUT06A[1]	32.41	45.80	13.39	41%	152.13	180.86	19%
OUT06[2]	45.73	44.08	-1.65	-4%	179.82	184.40	3%
TSHL01[2]	92.28	90.85	-1.43	-2%	517.98	521.66	1%
OUT04A[1]	64.87	91.59	26.71	41%	323.49	526.90	63%
OUT04[1]	82.69	91.26	8.57	10%	374.19	528.81	41%
OUT03[2]	90.69	91.41	0.72	1%	516.26	540.68	5%
OUT02[2]	91.40	90.38	-1.02	-1%	519.53	544.68	5%
TSOUT02[2]	100.00	76.40	-23.60	-24%	541.13	465.98	-14%
TSOUT01A[2]	99.20	76.87	-22.33	-23%	582.08	466.22	-20%
TSOUT01B[2]	44.66	40.36	-4.30	-10%	265.30	233.82	-12%

[1]Isco flow meter

[2]FlowShark meter

Meters OUT06A and OUT06 are located on the 99-inch Sewer that conveys flow from the Eastern Avenue Pump Station to the Outfall Sewer. OUT06A is located near the upstream end of the 99-inch Sewer close to the connection of the force main from the pump station. OUT06 is located near the downstream end of the 99-inch Sewer before connecting to the Outfall Sewer. The average dry weather flow in the 99-inch Sewer is approximately 26 MGD, but the flow is highly variable because the flow pattern is dominated by the pump station operations (typically varying from 10 to 40 MGD). The incremental flow from SSAs in the Outfall Sewershed between OUT06A and OUT06 is relatively small (only 0.2 MGD); therefore, the total flow at the two meters is essentially the same. The simulated flows match the measured flow at OUT06 very well because that data was used as the input boundary condition. The simulated flows at OUT06A are higher than the measured flows (simulated peak flow is 41% greater and volume is 19% greater than measured). A FlowShark meter was used at OUT06 and the data appear reasonable. An Isco meter was used at OUT06A; the data often contain intermittent periods of zero velocity when the pump station flows are at a minimum. The data at OUT06 is a better record of the flows in the 99-inch Sewer; therefore, it used as the inflow boundary condition data.

Meter TSHL01 is a FlowShark meter located near the upstream end of the Outfall Sewer after the confluence of flows from the High Level/Jones Falls sewersheds and the 99-inch sewer from the Low Level sewershed. The average dry weather flow is approximately 74 MGD. This data was used to develop the input boundary condition flows, consequently the simulated and measured data agree very closely.

Meters OUT04A and OUT04 are Isco meters located on the Outfall Sewer. The measured velocities (and consequently the recorded flow rate values) are consistently lower than values at neighboring meters (TSHL01 upstream and OUT03 downstream, both of which are FlowShark meters). It is the opinion of the hydraulic modeling engineers that the flow data at OUT04A and OUT04 have a low bias. It is assumed that the depth data is reasonable and that the flow pattern is realistic, but that measured flow values are lower than actual flows.

Meters OUT03 and OUT02 are FlowShark meters located along the Outfall Sewer along Monument Street and Lombard Street, respectively. The simulated flows match the measured flows very well at both meter sites. OUT02 is located just upstream of the chamber that allows flow to divide between the 132-inch Outfall Sewer and the 114-inch Relief Sewer. The average dry weather flow at OUT02 is approximately 78 MGD.

Flow from the Herring Run sewershed enters the model at the upstream end of the 114-inch Relief Sewer; the average dry weather flow at meter HR01 is approximately 18 MGD. Flow from the Dundalk sewershed enters the Outfall Sewer just downstream of a cross connection pipe between the Outfall and Relief Sewers, the average dry weather flow at meter TSDU03 is approximately 4 MGD. Based on this information, the sum of the flows from Herring Run, Dundalk and the Outfall Sewershed is approximately 100 MGD; this flow is conveyed by the parallel pipes (Outfall and Relief) to the Baltimore County Line which is the downstream end of the model.

Meters TSOUT01A and TSOUT01B are FlowShark meters located on the Outfall and Relief Sewer, respectively, near the Baltimore County Line. The balance of flow between the two pipes is very sensitive to the water level boundary condition defined at the Baltimore County Line (the downstream nodes of model). In general the level, velocity, and flow data recorded for TSOUT01A and TSOUT01B are reasonable. The flow at both meter sites is regulated by the water level at the Back River WWTP. The flow at the County Line is subject to backwater conditions from the plant; the depth and velocity relationship does not follow the normal Manning's relationship for open channel flow (the depths are deeper and the velocities are slower than normal flow). This backwater influence is also apparent in the data for all of the major trunk sewer meters.

The depth data at TSOUT01A and TSOUT01B can be converted to water levels assuming a pipe invert at the meter site. The derived water level data can be used for the downstream water level boundary condition at the outlet nodes of the InfoWorks™ model. During the calibration period, the water level in TSOUT01A is typically 0.4 feet higher than the water level in TSOUT01B; this difference is approximately 5% of the depth measurement values. Even though the difference is within an acceptable range of meter accuracy, it is critically important in determining the balance of flow between the Outfall and the Relief Sewers. The lower level boundary condition on the Relief Sewer draws the majority of the flow to the Relief Sewer and a lesser amount by the Outfall Sewer. The flow data does not support this balance of flow; the data indicates that approximately two thirds of the flow is conveyed by the Outfall Sewer and one third by the Relief Sewer.

Extended data was collected at these two meter sites for another year after the calibration period (until May 2008). During this extended period, the level data at the two meters is much closer, frequently recording essentially equal water level values. Therefore, the Joint Venture chose to use the level data for TSOUT01A as the downstream boundary condition for both the Outfall and Relief Sewers; this produced a realistic balance of flow between the two pipes.

In addition to the balance of flow between the Outfall and Relief Sewers, there is some uncertainly with the magnitude of the measured flows. The measured average dry weather flows are 83 MGD at TSOUT01A and 38 MGD at TSOUT01B; the sum of the flows is 121 MGD. For comparison, the simulated average dry weather flows are 67 MGD at TSOUT01A (19% less than measured) and 33 MGD at TSOUT01B (13% less than measured); the sum of the simulated flows is 100 MGD (17% less than measured).

Meter TSOUT02 is FlowShark meter located on the Outfall Sewershed just downstream of the connection from the Dundalk Sewershed. The flow at TSOUT02 and TSOUT01A are, in principle, equal flows. The measured average dry weather flow at TSOUT02 is 77 MGD, which is 6 MGD less than the measured flow at TSOUT01A. This further supports the assumption that meter TSOUT01A has a high bias in the measured flow values.

The simulated flows are consistent with the sum of the measured flows entering the parallel pipes from Herring Run, Dundalk, and the Outfall Sewershed (which is 97 MGD). Therefore, the calibration was defined to agree with as many meter sites as possible; in this case, however, the differences can be seen most clearly in the percent difference between simulated and measured values at TSOUT01A and TSOUT1B. In reality, the uncertainty could be (and likely is) shared between the various meters in the vicinity of the parallel sewers. The model configuration is, in the judgment of the engineers, a realistic representation of the flows and boundary conditions. The places where the difference between the simulated and measured values exceeds the calibration criteria are an acceptable compromise. This discussion of the dry weather flow response is intended to assist in a proper interpretation of the wet weather calibration results.

4.2.3. QA/QC Analysis

A wide variety of checks were performed on the model during model development to support QA/QC analysis of the model. These checks tested the sensitivity to model parameters and boundary condition assumptions. In all cases, the objective of the checks was to determine that the model response was a reasonable and realistic representation of the actual hydraulic response to flows generated within and outside of the Outfall Sewershed. A number of these QC checks are reflected in the discussion of the dry weather flow results in the paragraphs above.

4.3. Wet-Weather Calibration

The wet weather calibration seeks to determine parameters that characterize the response of the sewer systems to wet weather conditions that cause I/I. During the 12-month calibration period (May 2006 to May 2007) there were 29 wet weather events identified as global storms. Not all of these events produced a recognizable wet weather response in the sewer collection system. In general there are two types of significant wet weather events: (1) those that are driven by high intensity rainfall of a relatively short duration and (2) those that are driven by low intensity, longer duration rainfall. Because the modeling system chosen for this effort does not account for the influence of variable soil moisture storage, the simulated flows can either be calibrated to better match the short/high intensity storms or the longer/low intensity storm. The limitations of the modeling approach can not account for a wide variety of hydrologic conditions. Preference is given in this calibration to short/high intensity storms which drive the highest peak flows. This was chosen because the model will be subsequently applied to the evaluation of the hydraulic capacity of the collection system; therefore, it is more important to model peak flows accurately than to simulate the volume of events.

4.3.1. Calibration Criteria – Wet Weather

The wet weather calibration criteria from the BaSES manual Section 7.5.2 are summarized in Table 4-4. In addition to flow related comparison (peaks and volumes), there are also criteria to evaluate the depth of flow. For pipes that are not surcharged, the simulated depth of flow should be within 4 inches of the measured depth of flow. For surcharged pipes the criteria depends on the size of pipe and whether the simulated flows are greater than or less than the measured depths.

Table 4-4: Wet Weather Validation Criteria

Simulated response	Percent difference from observed measurements
Peak Flow Rate	Within –10% and + 25%
Volume of Flow (assume duration from the start of rainfall to 2 days after rainfall ends)	Within –10% and + 20%
Depth of Flow in Surcharged Pipes: For pipes 21-inch diameter and larger For pipes smaller than 21-inch diameter	 Within -4 inches and +18 inches Within -4 inches and +6 inches
Depth of Flow in Unsurcharged Pipes	Within 4 inches
Shape and timing of hydrographs	Should be similar

4.3.2. Calibration Events (Global Storms)

Table 4-5 lists the 29 wet-weather events to be used for sewershed flow calibration. These historic storms were selected by the City because of the following characteristics:

- Wide geographic distribution throughout the City and upper and lower basins of the sewersheds;

- Distinct rain response (i.e., flow increases by at least 50 percent of the average dry day flow);
- Acceptable scatter graph analysis (a graph of flow meter data showing velocity vs. depth of flow); and,
- Data represent the flow conditions from May 2006 to April 2007.

Table 4-5. Primary Storm Events for Calibration

Rainfall Start Time	Rainfall End Time	Storm Period Length (minutes)	R1 Period Length (minutes)	R2 Period Length (minutes)	Total Rainfall Depth (inches)
05/11/2006 12:00	05/11/2006 22:00	2,160	1,440	60	1.5
05/14/2006 23:00	05/15/2006 16:00	2,880	1,440	60	0.6
06/02/2006 19:00	06/03/2006 06:00	1,440	1,440	1,440	1.3
06/19/2006 14:00	06/19/2006 16:00	1,440	1,440	1,440	0.4
06/24/2006 13:00	06/24/2006 22:00	1,080	60	60	1.0
06/25/2006 04:00	06/25/2006 22:00	8,640	60	60	7.0
07/05/2006 11:00	07/06/2006 06:00	5,760	60	60	2.6
07/22/2006 14:00	07/23/2006 00:00	1,440	1,440	1,440	0.8
09/01/2006 06:00	09/02/2006 17:00	3,600	60	60	3.0
09/05/2006 02:00	09/05/2006 17:00	2,880	1,440	60	2.1
09/14/2006 01:00	09/14/2006 21:00	4,320	60	60	1.8
09/28/2006 17:00	09/28/2006 22:00	2,160	60	60	0.9
10/05/2006 20:00	10/06/2006 16:00	7,200	60	60	1.8
10/17/2006 07:00	10/18/2006 02:00	2,160	60	60	1.0
10/19/2006 20:00	10/20/2006 11:00	2,160	60	60	0.6
10/27/2006 15:00	10/28/2006 08:00	3,600	60	60	2.2
11/07/2006 20:00	11/08/2006 15:00	3,600	60	60	1.6
11/16/2006 08:00	11/16/2006 17:00	7,200	60	60	2.4
11/22/2006 11:00	11/23/2006 03:00	5,760	60	60	1.1
12/22/2006 12:00	12/23/2006 03:00	3,600	60	60	1.3
12/25/2006 12:00	12/26/2006 01:00	4,320	60	60	0.7
12/31/2006 16:00	01/01/2007 14:00	4,320	60	60	1.0
01/07/2007 17:00	01/08/2007 16:00	4,320	60	60	0.9
03/01/2007 18:00	03/02/2007 09:00	5,760	60	60	1.0
03/15/2007 16:00	03/16/2007 17:00	8,640	60	60	2.6
03/23/2007 13:00	03/24/2007 10:00	4,320	60	60	0.4
04/04/2007 03:00	04/04/2007 09:00	1,440	60	60	0.6
04/11/2007 21:00	04/12/2007 06:00	2,880	60	60	1.1

Table 4-5. Primary Storm Events for Calibration					
Rainfall Start Time	Rainfall End Time	Storm Period Length (minutes)	R1 Period Length (minutes)	R2 Period Length (minutes)	Total Rainfall Depth (inches)
04/14/2007 19:00	04/16/2007 03:00	7,200	60	60	2.9

4.3.3. Comparison of Metered and Modeled Results

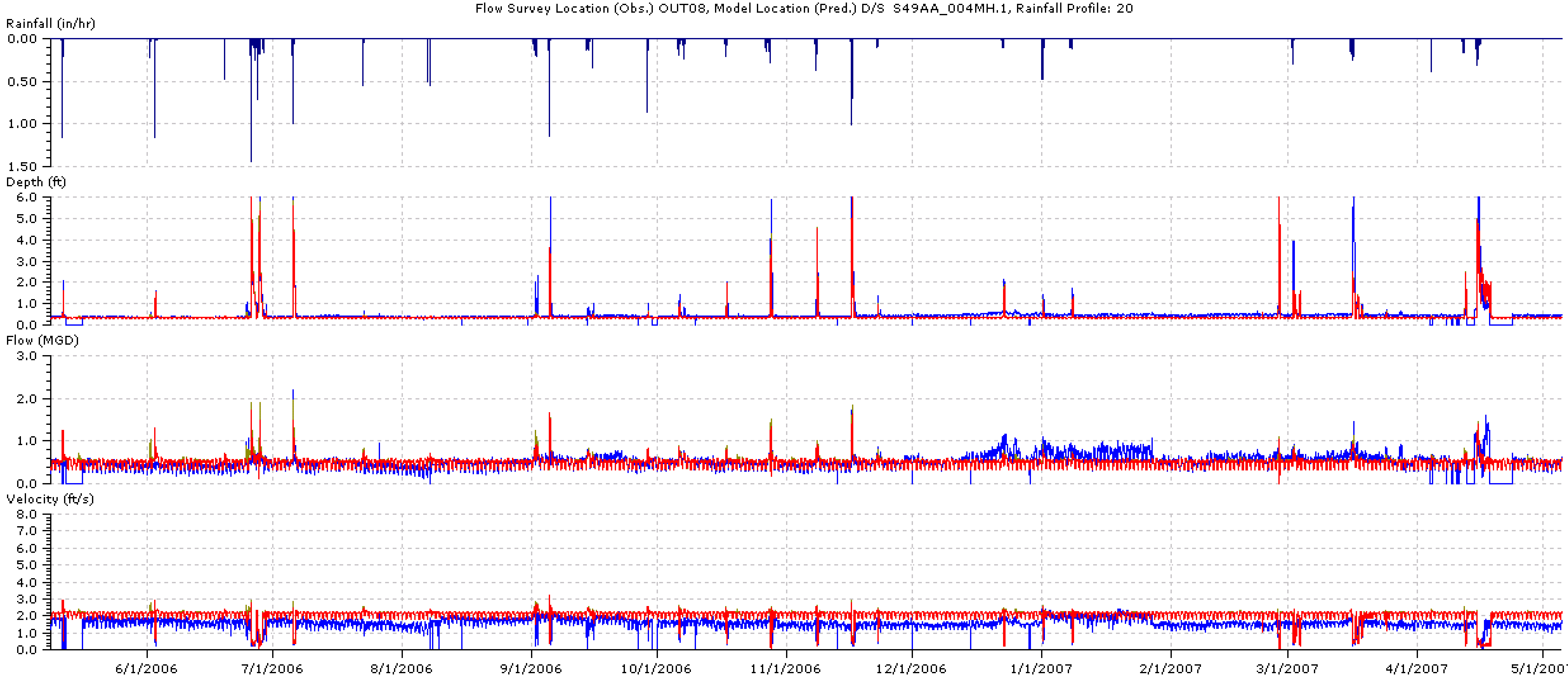
Sample results are presented below along with an explanation of the format of the presentation. Appendix D contains a complete series of graphics for all meter sites. The calibration results are summarized with a time series plot and three statistical plots that compare the simulated results to the measured values. The time series plots show a large scale view of the calibration performance. The results can be viewed in electronic form in the InfoWorks™ software to see greater detail for specific events.

Time series plots were created using the reporting tools of the InfoWorks™ software. The 12-month duration of the simulations was from May 2006 to May 2007; these are continuous simulations including dry and wet weather periods. One of the simulations used the CALAMAR radar rainfall data which is available for most of the global storms. The other simulation is based on the ground rain gauge data in Sliicer; this is a continuous record of rainfall with data for the entire period. The Sliicer rainfall data has a 30-minute time step and it represents a composite rainfall record for each meter basin (developed from an inverse distance squared composition of the rain gauges in the vicinity of each meter basin). Most of the larger events are calibrated using the CALAMAR radar rainfall simulation; when necessary, other events are based on the ground based rain gauge data. Figure 4-1 is a time series plot for meter OUT08 which monitors flow in a 24-inch branch sewer. The rainfall intensity is plotted at the top of the graph (with the values increasing towards the bottom of the page) to help identify the timing and nature of the wet weather event. Below the rainfall plot are traces of water depth, flow, and velocity. The observed (measured) values are plotted in blue. The simulated values are plotted in red for the simulation using the CALAMAR rainfall data and in a greenish-tan color for the simulation using the ground based rain gauge data. In most cases, the radar rainfall simulation results plot on top of the rain gauge simulation results; therefore, little of the greenish traces is visible.

Figure 4-2 is the same data, but the view is zoomed in to the June through July 2006 period to display the hydrographs for three wet weather events. The small rainfall event on 6/19/2006 does not produce any significant wet weather response in the collection system. For both the measured and simulated value the dry weather pattern is essentially unchanged during the event. The large, long duration event that began on 6/25/2006 had two episodes of peak flow. High, surcharged water levels in the Outfall Sewer caused surcharging in the 24-inch branch sewer at the location of meter OUT08. During the surcharge periods, the water levels are above the crown of the pipe and the velocities drop significantly from the open channel flow conditions. The third event on 7/6/2006 is also influenced by surcharging in the Outfall Sewer.

Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 17 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

Flow Survey Location (Obs.) OUT08, Model Location (Pred.) D/S S49AA_004MH.1, Rainfall Profile: 20



	Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
	Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain	34.755	1.434	0.004							
Obs.				0.000	6.931	0.000	2.193	178.133	0.000	2.437
...>ModelSim>A18>GaugeRain				0.282	7.026	-0.137	1.972	182.474	-0.065	3.213
...>ModelSim>A18>RadarRain				0.282	6.925	-0.239	1.710	179.548	-0.113	3.230

Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 17 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
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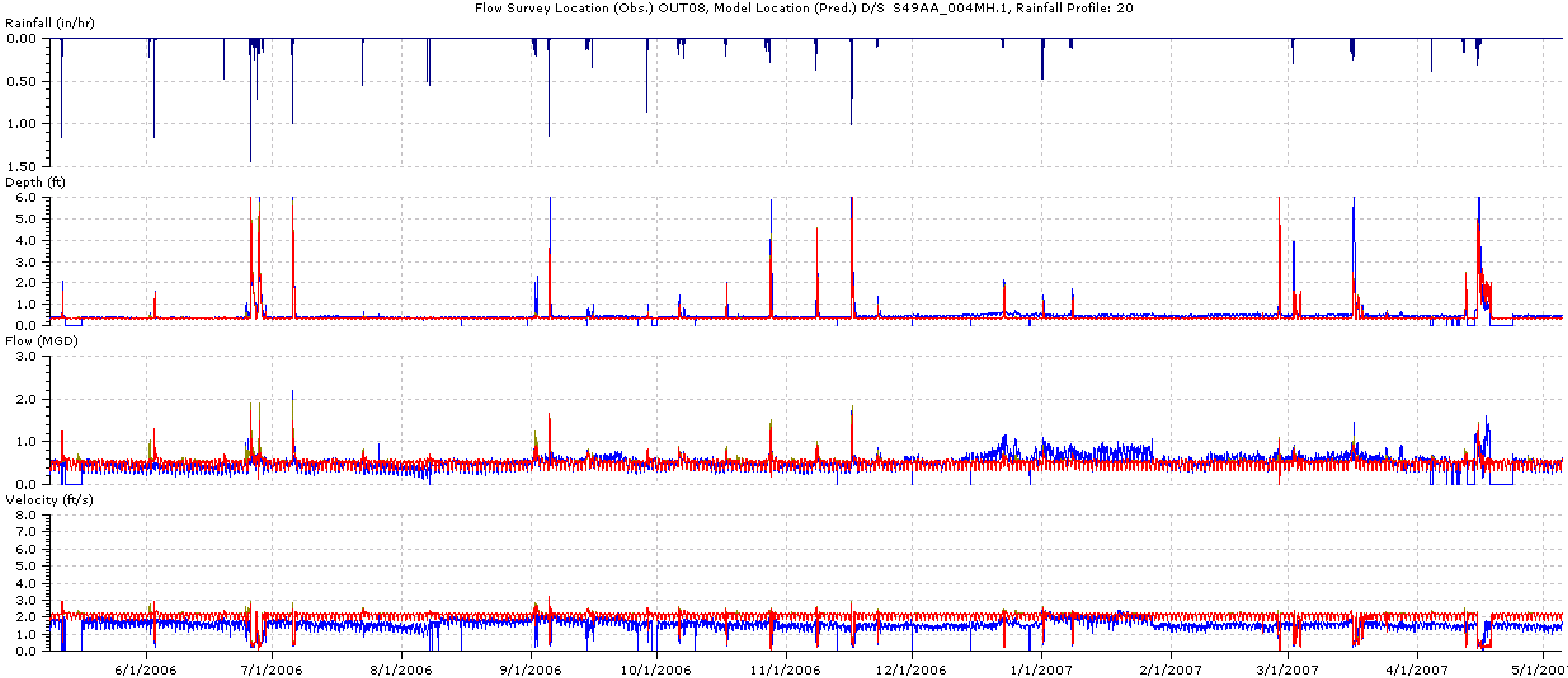
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

Flow Survey Location (Obs.) OUT08, Model Location (Pred.) D/S S49AA_004MH.1, Rainfall Profile: 20

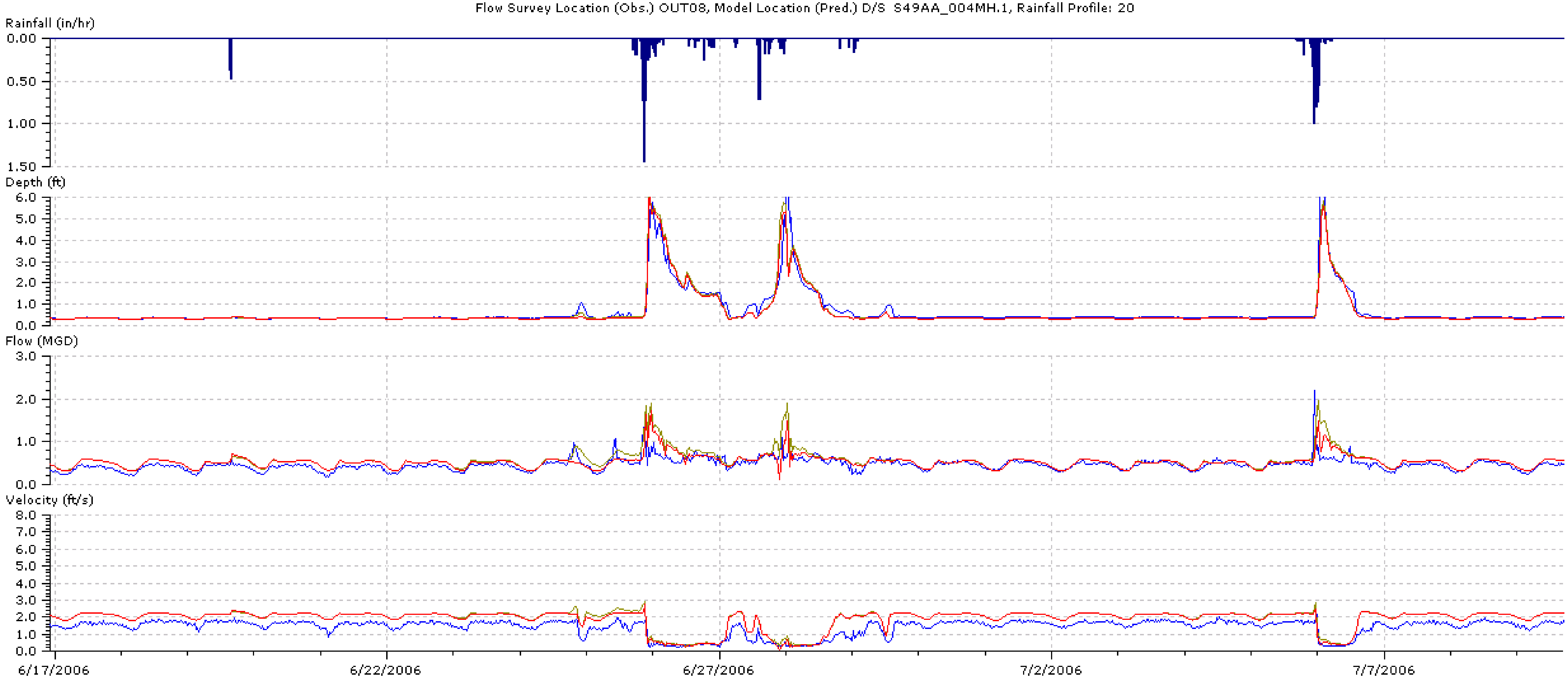


	Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
	Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain	34.755	1.434	0.004							
Obs.				0.000	6.931	0.000	2.193	178.133	0.000	2.437
...>ModelSim>A18>GaugeRain				0.282	7.026	-0.137	1.972	182.474	-0.065	3.213
...>ModelSim>A18>RadarRain				0.282	6.925	-0.239	1.710	179.548	-0.113	3.230

Figure 4-1. Time series plot at meter OUT08 for the period of record.

Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 17 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

Flow Survey Location (Obs.) OUT08, Model Location (Pred.) D/S S49AA_004MH.1, Rainfall Profile: 20



	Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
	Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain	6.730	1.434	0.012							
Obs.				0.275	6.931	0.182	2.193	10.602	0.227	2.157
...>ModelSim>A18>GaugeRain				0.282	6.229	0.313	1.972	12.808	0.300	2.928
...>ModelSim>A18>RadarRain				0.282	6.100	0.107	1.710	12.119	0.050	2.783

Figure 4-2. Time series plot at meter OUT08 for June and July 2006.

The statistical plots are a concise summary of the results that show the correlation between simulated results and observed values. Using meter OUT08 as an example, Figures 4-3, 4-4, and 4-5 are statistical plots for peak depth, peak flow, and volume for the wet weather events. Each statistical plot has a one-to-one line that represents perfect correlation between simulated and observed values. Upper and lower reference lines on the statistical plots show the envelope of the calibration criteria. When the pipe is not surcharged, the calibration criteria for peak depth is ±4 inches. When the pipe is surcharged, the calibration criteria is +18 inches and -4 inches because the pipe size is 24-inches. If the pipe diameter were less than 21 inches, the surcharged criteria would be +6 inches and -4 inches. Reference lines also mark the pipe crown to show surcharging when peak depth are greater than the pipe diameter. For the larger surcharged events, the simulation results are within the calibration boundaries. When the pipe is not surcharged, the simulated peak depths are generally greater than observed depths. For a few of the smaller events in the transition zone, the model tends to simulate surcharging conditions for some events that did not have observed surcharging.

Each statistical plot shows the data points and two regression lines that have been fitted to the data points. The solid black regression line is associated with a regression equation of the form **Ax + B**. This regression does not force the equation to pass through the origin. The equation and the goodness of fit correlation coefficient, R^2, are printed on the graph in black font.

The dotted red regression line is associated with a regression equation of the form **Ax**, which assumes a y-intercept of zero. The equation and the goodness of fit correlation coefficient, R^2, are printed on the graph in red font. The slope of the line (represented by coefficient A) is an overall indication of how close the simulated values are to the observed values. The correlation coefficient, R^2, is an indication of how well the model fits for a variety of wet weather conditions.

For meter OUT08, the slope of the dotted red line for peak flow is 0.99, which means that the simulated peak flows are very close to the observed values overall. The slope of the dotted red line for the event volume is 1.05, which means that the simulations over predict the event volume by 5% on average. Reference lines for the statistical plots of peak flow define the criteria of +25% and –10%. On the statistical plots of event volume the criteria is +20% and -10%.

Overall, the calibration of SSAs in meter basin OUT08 produce simulated results that are a realistic representation of the actual system hydraulics.

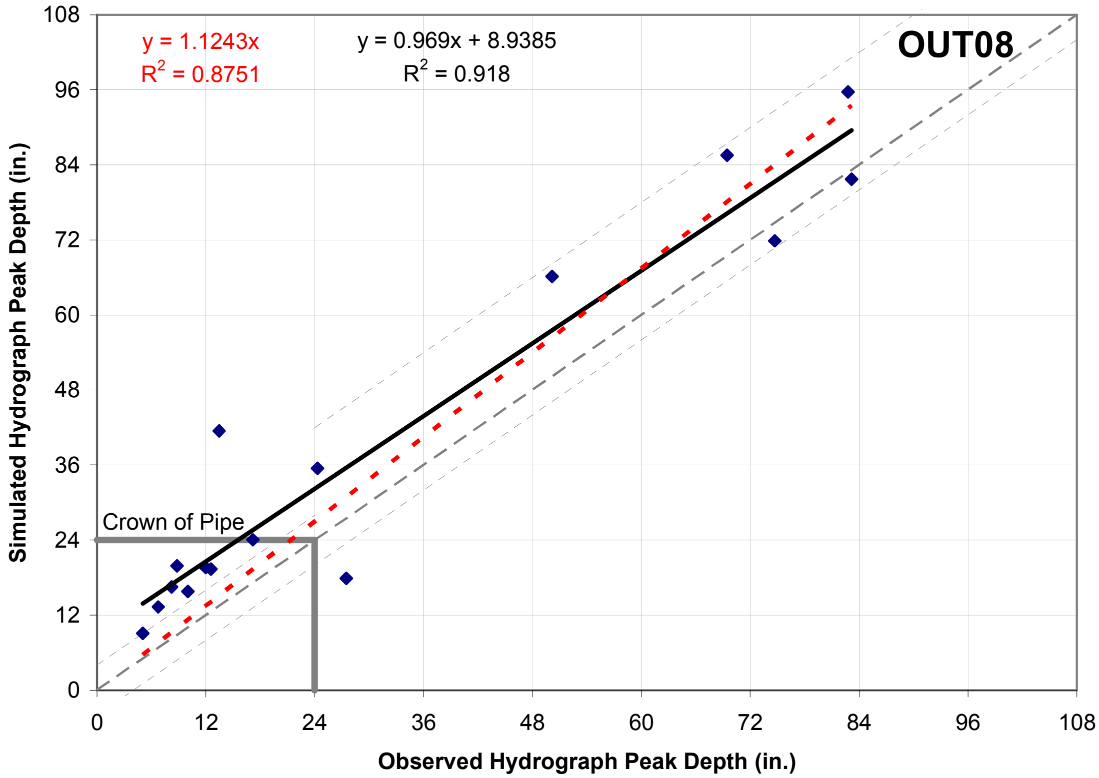


Figure 4-3. Statistical plot of peak depth for OUT08.

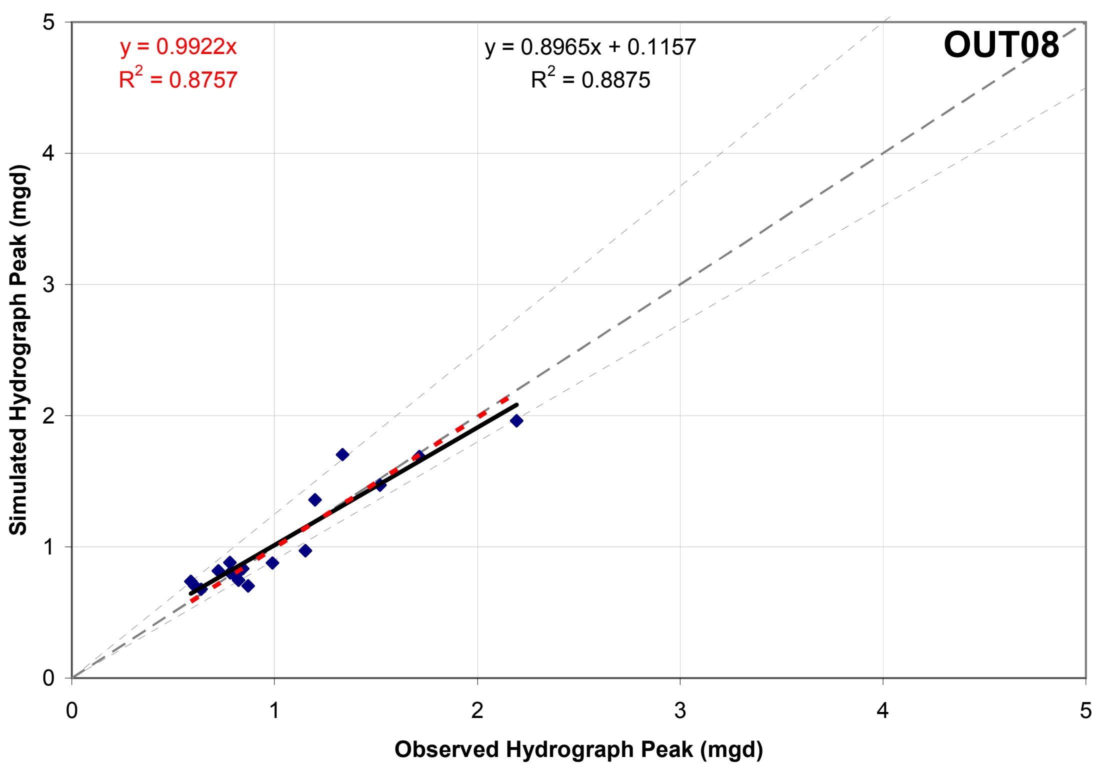


Figure 4-4. Statistical plot of peak flow for OUT08.

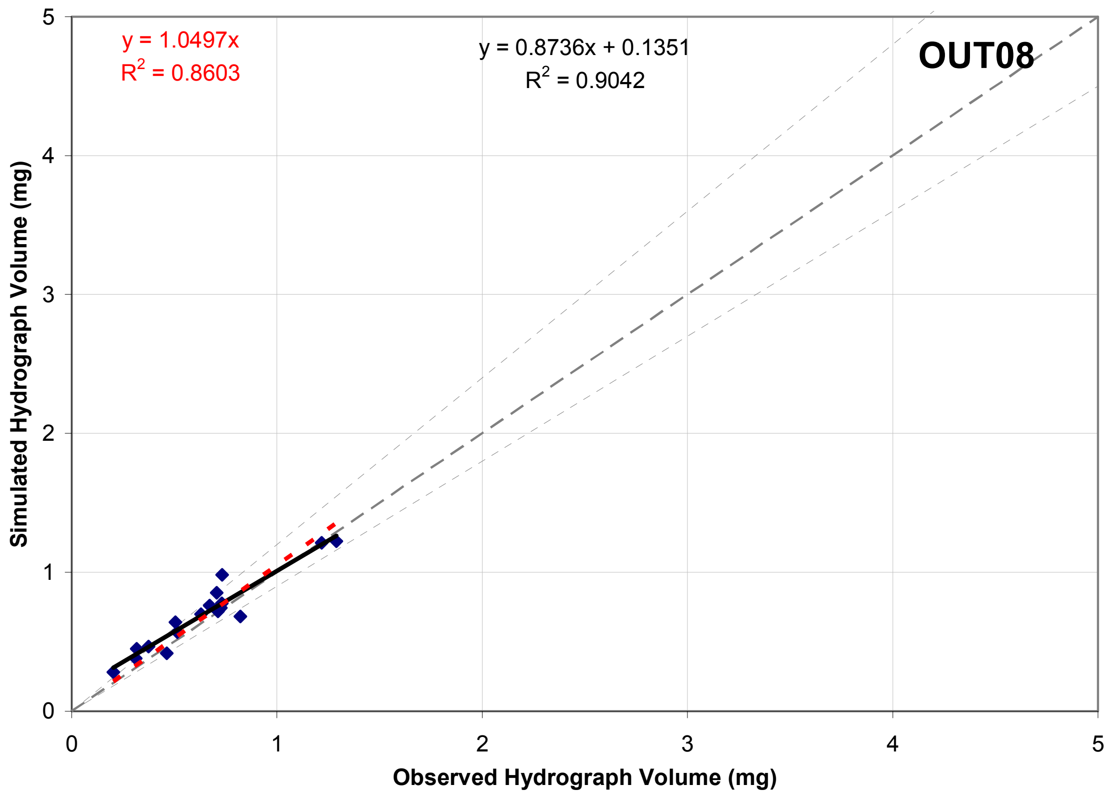


Figure 4-5. Statistical plot of event volume for OUT08.

Table 4-6 is a very brief summary of the wet weather calibration results. For most of the meters, the average trends of simulated values (as represented by the slope of the dotted red lines) are within the calibration criteria. For meters OUT04, OUT04A, and OUT06A, the measured values are unrealistically low (compared to neighboring meters) and this is the reason that the simulated values are not within the calibration criteria. For TSOUT01A and TSOUT02 the measured values may be low for peak flow and volume. The simulated values at these sites are very sensitive to the assumed water level boundary conditions used at the Baltimore County line (as discussed above in the dry weather calibration discussion). The brief summary in Table 4-6 is intended to point the reader to Appendix D to view the results in more detail. In some of the cases, it is necessary to view the results in the InfoWorks™ software to see hydrographs for specific wet weather events.

For meter HL03, the simulated peak flow values are consistent with peak flows upstream at meter HL04, but the measured peak flows are much less than the simulated values. High water levels in the Outfall Sewer cause surcharging at meter HL03; during these conditions, the measured peak flow values are unrealistically low.

Table 4-6. Summary of Wet Weather Calibration			
Metershed	Peak Depth	Peak Flow	Volume
HL01	OK	OK	OK
HL02	OK	OK	OK
HL02B	OK	OK	OK
HL03	OK	Measured Values Low	OK
HL04	OK	OK	OK
HL05	OK	OK	OK
OUT01	OK	OK	OK
OUT02	OK	OK	OK
OUT03	OK	OK	OK
OUT04	OK	Measured Values Low	Measured Values Low
OUT04A	OK	Measured Values Low	Measured Values Low
TSHL01	OK	OK	OK
OUT05	N/A	N/A	N/A
OUT06	OK	OK	OK
OUT06A	OK	Measured Values Low	Measured Values Low
OUT07	OK	OK	OK
OUT08	OK	OK	OK
OUT09	OK	OK	OK
TSOUT02	Measured Values Low	Measured Values High	Measured Values High
TSOUT01A	OK	Measured Values High	Measured Values High
TSOUT01B	OK	OK	OK

5. SUMMARY AND CONCLUSIONS

Rainfall and flow monitoring data provides the foundation for model calibration. The radar rainfall data (CALAMAR) was used (when available) to drive the model simulations. Ground based rain gauge data was also used to run the simulations; this result provides a check on the radar rainfall simulation and it fills in a few gaps where the radar rainfall data is not available.

The flow meter data from the Sliicer server was imported into the InfoWorks™ model. The Sliicer program was used to develop the initial estimates of the R-factor that defines the volume of I/I relative to the rainfall. The Sliicer program stores and manipulates the data on the meter basin scale. The calibration parameters in the InfoWorks™ model apply to the subcatchments; therefore, the calibration parameters are refined in the InfoWorks™ model for the final calibration before validation.

The model development process consists of building the network of pipes, defining the flow generation parameters in the subcatchments, and establishing the boundary conditions for inflows and downstream water levels. The Macro Model provided the first source of network data. This model network was expanded to include all pipes 10-inches and larger in the Outfall Sewershed. The manhole positions and pipe connectivity and invert data were refined using the field survey data. Sediment levels in the large diameter trunk sewers were determined from sonar-based sediment survey data.

Subcatchments are nominally the same as the SSAs; when necessary, SSAs were redefined and subdivided as necessary to be compatible with the model pipe network. Subcatchment parameters were defined by the waste water flow values and calibrated I/I components; most important parameters are:

- Contributing sewered area
- Base wastewater flow (given)
- Dry weather infiltration (to match the average dry weather flow)
- R-value (to match the volume of I/I)
- Width of the subcatchment (to match the wet weather peak flow)

SSAs along the branch sewers in the Outfall Sewershed are calibrated using the meters located on the branch sewers. The remaining SSAs tributary to the major trunk sewers were assigned typical parameters to generate reasonable dry and wet weather flows. Meters located on the major trunk sewers are used to calibrate the large scale hydraulic properties and responses of the model (such as roughness, sediment depth, boundary conditions, and water depth). Thus there are two distinct applications of flow meter data to the model calibration: the smaller branch meters are used to calibrate the SSA flow generation parameters, and the larger trunk meters are used to calibrate the large scale hydraulic parameters.

In most cases, the simulation results match the measured values for water depth, peak flow, and volume within the calibration criteria defined in the BaSES manual. Most of the meter sites for which the difference exceeds the calibration criteria can be attributed to uncertainties in the measured flow meter data.

Simulation results are very sensitive to the assumed boundary conditions. The upstream boundary conditions define the inflows from the upstream sewersheds (High Level/Jones Falls, Low Level, Herring Run, and Dundalk); measured data was used to define these upstream boundary condition flows. The downstream boundary conditions are the water levels in the Outfall and Relief Sewers at the Baltimore County line (defined by flow meters TSOUT01A and TSOUT01B). The calibration results at flow meter sites located along the large diameter trunk sewers are highly sensitive to the assumed boundary conditions. The calibration results at flow meter sites located on the smaller branch sewers are less sensitive to the boundary conditions, except for when high water levels in the trunk sewer create surcharged conditions in the branch sewer meter locations. The primary conclusion from this comparison is that the model is properly routing the input flow boundary conditions from the upstream sewersheds (that is, the measured flows from High Level, Jones Falls, Low Level, Herring Run, and Dundalk).

In summary, the quality of the model calibration results can be reviewed by examining the time series plots and the statistical plots in Appendix D. The simulation results along the branch sewers demonstrate that the model configuration is generating flow for dry and wet weather conditions that is a realistic and suitable to evaluate the hydraulic capacity of the branch sewers. The simulation of results along the major trunk sewers shows that the model is properly routing flows from the upstream sewersheds through the Outfall and Relief Sewers to the County line. The model is ready to be used for the "Baseline Analysis and Capacity Assessment" and to develop and evaluate capacity alternatives once combined by the City's Technical Program Management team with calibrated models from upstream sewersheds.

6. REFERENCES

City of Baltimore, **Baltimore Sewer Evaluation Standards (BaSES manual)**, v. 08.03, May 2008, prepared for the City of Baltimore, Department of Public Works – Bureau of Water and Wastewater.

KCI Technologies (2007), **Current and Future Dry Weather Base Sanitary Flows, Subtask 8.5**, Draft December 2007, prepared for the City of Baltimore, Department of Public Works – Bureau of Water and Wastewater.

EA Engineering Science and Technology, Transmittal No. 00007, P9 Outfall Sewershed Study, 2/14/2008, Contained a spreadsheet with the of the Current and Future Dry Weather Base Sanitary Flows, (*spreadsheet* **SSA Flow Projections Rev 0.xls)**

Appendices

Appendix A: Meter Basin Characteristics

Appendix B: Subcatchment Characteristics

Appendix C: List of Electronic Files

Appendix D: Calibration Results

Attachments

Attachment 1: Electronic Files on CD

Appendix A: Meter Basin Characteristics

Appendix A: Meter Basin Characteristics

The meterbasin parameters that define the generation of dry and wet weather flows are:

- Contributing area
- Base Sanitary Flow (BSF)
- Groundwater Infiltration (GWI)
- R-factor (SWMM model, I/I volume as a percent of rainfall during wet weather)

The meterbasin values listed in Table A were later decomposed into subcatchment parameters in proportion to subcatchment contributing area. Meters on the branch sewers were used to develop the calibration parameters for subcatchments tributary to the branch sewers.

Meterbasins on the major trunk sewers, including tributary branch sewers that are not directly monitored were assigned nominal values. Values for BSF were given by the City and GWI is assumed to be equal to BSF. The R-factor is assumed to be 10%; the assumption is conservative and will produce large peak flows in the branch sewers. This assumption will be re-examined during the baseline capacity evaluation if capacity issues are found to exist.

Table A: Meterbasin Flow Generation Parameters

Meterbasin	Area (acres)	Contributing Area (acres)	BSF (MGD)	GWI (MGD)	R-factor	Calibration Source
HL01	228.7	228.7	0.141	0.159	2.0	HL01 meter data
HL02	106.3	106.3	0.205	0.335	8.0	HL02 meter data
HL02B	15.2	15.2	0.030	0.030	12.0	HL02B meter data
HL03	86.4	86.4	0.147	0.133	3.0	HL03 meter data
HL04	128.8	128.8	0.185	0.035	7.5	HL04 meter data
HL05	373.5	168.2	0.256	0.034	6.5	HL05 meter data
Downstream of OUT01	29.4	29.4	0.018	0.057	10.0	OUT01 parameters
OUT01	171.3	134.0	0.095	0.305	10.0	OUT01 meter data
OUT02	467.6	437.4	0.144	0.144	10.0	Given BSF Assumed nominal I/I parameters
OUT03	194.3	194.3	0.338	0.338	10.0	Given BSF Assumed nominal I/I parameters
OUT04	54.4	54.4	0.106	0.106	10.0	Given BSF Assumed nominal I/I parameters
OUT05	33.8	33.8	0.084	0.084	10.0	Given BSF Assumed nominal I/I parameters
OUT06	99.1	99.1	0.246	0.246	10.0	Given BSF Assumed nominal I/I parameters
OUT07	91.4	91.4	0.256	0.004	13.0	OUT07 and OUT09 meter data
OUT08	126.9	126.9	0.347	0.133	5.0	OUT08 meter data
TSOUT01A	38.8	38.8	0.022	0.022	10.0	Given BSF Assumed nominal I/I parameters
TSOUT01B	68.2	68.2	0.002	0.002	10.0	Given BSF Assumed nominal I/I parameters
TSOUT02	3.3	3.3	0.002	0.002	10.0	Given BSF Assumed nominal I/I parameters

Appendix B: Subcatchment Characteristics

Appendix B: Subcatchment Characteristics

The subcatchment parameters that define the generation of dry and wet weather flows are:

- Contributing area
- Base Sanitary Flow (BSF)
- Groundwater Infiltration (GWI)
- R-factor (SWMM model, I/I volume as a percent of rainfall during wet weather)
- Width (SWMM model, controls the peak flow rate)
- Slope (SWMM model)
    - Subcatchments in branch sewer meter basins: Slope is calculated using the ground slope of the first pipe segment (with the 0.1 suffix) attached to the load point node. If this value is less than 0.1 percent then a value of 0.1 percent is assumed.
    - Subcatchments in major trunk sewer meter basins (including tributary branch sewer subcatchments that are not directly monitored): Slope assumed equal to 1% for all subcatchments
- Depression storage (equal to 0 inches for all subcatchments)
- Manning's roughness for surface flow(SWMM model, equal to 0.017 for all subcatchments)

Table B: Subcatchment Flow Generation Parameters

Meter Basin	Subcatchment	Area (acre)	Contributing Area (acre)	BSF (MGD)	GWI (MGD)	R-factor	Width (ft)
HL01	36-04-00-00-A	104.52	104.52	0.0313	0.0740	2.0	9.6
HL01	36-04-00-00-B	40.2	40.2	0.012	0.028	2.0	3.6
HL01	36-04-00-00-C	4.41	4.41	0.0013	0.0020	2.0	0.4
HL01	36-05-00-00	43.45	43.45	0.0345	0.0300	2.0	4.0
HL01	36-06-00-00	36.10	36.10	0.0623	0.0250	2.0	3.2
HL02	39-01-00-00-B	3.80	3.80	0.0076	0.0120	8.0	0.5
HL02	39-01-00-00-C	16.70	16.70	0.0334	0.0526	8.0	2.8
HL02	39-01-00-00-D	22.88	22.88	0.0458	0.0720	8.0	3.7
HL02	39-01-00-00-E	12.61	12.61	0.0253	0.0397	8.0	2.1
HL02	39-01-00-00-F	2.44	2.44	0.0049	0.0077	8.0	0.4
HL02	39-02-00-00	47.91	47.91	0.0884	0.1508	8.0	7.7
HL02B	39-01-01-00-A	15.24	15.24	0.0297	0.0300	12.0	5.2
HL03	40-01-00-00	10.91	10.91	0.0256	0.0168	3.0	1.5
HL03	40-02-00-00-a-A	17.58	17.58	0.0282	0.0271	3.0	2.0
HL03	40-02-00-00-a-B	9.27	9.27	0.0149	0.0143	3.0	1.0
HL03	40-02-00-00-a-C	1.84	1.84	0.0030	0.0028	3.0	0.5
HL03	40-02-00-00-a-D	22.40	22.40	0.0359	0.0346	3.0	2.5
HL03	40-02-00-00-a-E	15.20	15.20	0.0244	0.0235	3.0	1.5

Table B: Subcatchment Flow Generation Parameters							
Meter Basin	Subcatchment	Area (acre)	Contributing Area (acre)	BSF (MGD)	GWI (MGD)	R-factor	Width (ft)
HL03	40-02-00-00-b	9.22	9.22	0.0148	0.0142	3.0	1.0
HL04	40-03-00-00	50.49	50.49	0.0776	0.0139	7.5	7.0
HL04	40-04-00-00-A	6.63	6.63	0.0094	0.0018	7.5	0.9
HL04	40-04-00-00-B	0.86	0.86	0.0012	0.0002	7.5	0.1
HL04	40-04-00-00-C	46.35	46.35	0.0658	0.0127	7.5	6.5
HL04	40-04-00-00-D	11.56	11.56	0.0164	0.0032	7.5	1.6
HL04	40-05-00-00-B	12.88	12.88	0.0142	0.0035	7.5	1.8
HL05	40-05-00-00-A	5.62	5.62	0.0000	0.0011	6.5	0.2
HL05	40-06-00-00-A	17.76	17.76	0.0374	0.0036	6.5	0.5
HL05	40-06-00-00-B	30.10	30.10	0.0526	0.0061	6.5	0.9
HL05	40-06-00-00-C	83.35	0.00	0.0000	0.0000	6.5	0.1
HL05	40-07-00-00	145.99	40.00	0.0647	0.0081	6.5	1.1
HL05	40-08-00-00-A	42.957	27	0.048	0.0055	6.5	0.8
HL05	40-08-00-00-B	47.67	47.67	0.0533	0.0097	6.5	1.4
Downstream of OUT01	27-01-00-00-A	13.28	13.28	0.0080	0.0257	10.0	2.7
Downstream of OUT01	27-01-00-00-C	16.08	16.08	0.0097	0.0312	10.0	3.2
OUT01	27-01-00-00-B	47.72	28.00	0.0168	0.0638	10.0	5.6
OUT01	27-02-00-00	94.99	94.99	0.0597	0.2165	10.0	10.0
OUT01	27-03-00-00	28.56	11.00	0.0200	0.0300	10.0	2.2
OUT02	34-01-00-00	15.64	5.00	0.0012	0.0016	10.0	0.1
OUT02	34-02-00-00-A	127.19	127.19	0.0646	0.0419	10.0	2.6
OUT02	34-02-00-00-B	18.82	18.82	0.0096	0.0062	10.0	0.4
OUT02	35-01-00-00	10.69	10.69	0.0009	0.0035	10.0	0.2
OUT02	35-01-01-00-A	9.74	0.00	0.0015	0.0000	10.0	0.1
OUT02	35-01-01-00-B	6.40	0.00	0.0010	0.0000	10.0	0.1
OUT02	35-01-01-00-C	62.22	62.22	0.0097	0.0205	10.0	1.3
OUT02	35-02-00-00-A	39.44	39.44	0.0058	0.0130	10.0	0.8
OUT02	35-02-00-00-B	1.59	1.59	0.0002	0.0005	10.0	0.0
OUT02	35-02-00-00-C	8.55	8.55	0.0013	0.0028	10.0	0.2
OUT02	35-03-00-00-A	13.61	13.61	0.0059	0.0045	10.0	0.3
OUT02	35-03-00-00-B	54.82	54.82	0.0237	0.0180	10.0	1.1
OUT02	36-01-00-00	3.43	0.00	0.0018	0.0000	10.0	0.1
OUT02	36-02-00-00	15.03	15.03	0.0026	0.0049	10.0	0.3
OUT02	36-03-00-00-A	32.59	32.59	0.0056	0.0107	10.0	0.7
OUT02	36-03-00-00-B	42.24	42.24	0.0072	0.0139	10.0	0.9
OUT02	36-03-00-00-C	5.58	5.58	0.0010	0.0018	10.0	0.1
OUT03	37-01-00-00	111.09	111.09	0.1521	0.1932	10.0	5.7
OUT03	37-02-00-00	21.35	21.35	0.0445	0.0371	10.0	1.1
OUT03	37-03-00-00-A	14.99	14.99	0.0354	0.0261	10.0	0.8
OUT03	37-03-00-00-B	23.45	23.45	0.0555	0.0408	10.0	1.2

Table B: Subcatchment Flow Generation Parameters							
Meter Basin	Subcatchment	Area (acre)	Contributing Area (acre)	BSF (MGD)	GWI (MGD)	R-factor	Width (ft)
OUT03	38-01-01-00	9.33	9.33	0.0221	0.0162	10.0	0.5
OUT03	39-01-00-00-A	10.78	10.78	0.0216	0.0187	10.0	0.6
OUT03	39-01-01-00-E	3.34	3.34	0.0065	0.0058	10.0	0.2
OUT04	39-01-01-00-B	5.247	5.247	0.0102	0.0102	10.0	0.2
OUT04	39-01-01-00-C	24.53	24.53	0.0479	0.0480	10.0	5.2
OUT04	39-01-01-00-D-1	7.81	7.81	0.0153	0.0152	10.0	0.3
OUT04	39-01-01-00-D-2	16.86	16.86	0.0329	0.0327	10.0	0.6
OUT05	41-02-00-00-A-1	28.87	28.87	0.0718	0.0718	10.0	1.0
OUT05	41-02-00-00-A-2	1.39	1.39	0.0035	0.0035	10.0	1.0
OUT05	41-02-00-00-A-3	0.67	0.67	0.0017	0.0017	10.0	1.0
OUT05	41-02-00-00-A-4	0.54	0.54	0.0012	0.0012	10.0	1.0
OUT05	41-02-00-00-A-5	2.36	2.36	0.0059	0.0059	10.0	1.0
OUT06	41-03-00-00-A	29.62	29.62	0.0782	0.0735	10.0	1.5
OUT06	41-03-00-00-B	8.75	8.75	0.0231	0.0217	10.0	0.4
OUT06	41-04-00-00-A	22.90	22.90	0.0544	0.0568	10.0	1.1
OUT06	41-04-00-00-B	3.86	3.86	0.0092	0.0096	10.0	0.2
OUT06	41-04-00-00-C	17.65	17.65	0.0419	0.0438	10.0	0.9
OUT06	41-04-00-00-D	16.36	16.36	0.0389	0.0406	10.0	0.8
OUT07	41-05-01-00-A	23.29	23.29	0.0615	0.0010	13.0	2.2
OUT07	41-05-01-00-B	26.16	26.16	0.0691	0.0011	13.0	2.6
OUT07	41-05-02-00	16.852	16.852	0.0501	0.0007	13.0	1.6
OUT07	41-05-03-00	25.13	25.13	0.0753	0.0011	13.0	2.4
OUT08	38-01-00-00	23.36	23.36	0.0531	0.0245	5.0	0.9
OUT08	38-02-00-00	19.40	19.40	0.0442	0.0204	5.0	0.8
OUT08	38-03-00-00	45.41	45.41	0.1377	0.0477	5.0	1.8
OUT08	38-04-00-00	18.28	18.28	0.0553	0.0192	5.0	0.7
OUT08	38-05-00-00	20.47	20.47	0.0564	0.0215	5.0	0.8
TSOUT01A	27-01-01-00	38.77	38.77	0.0216	0.0216	10.0	1.8
TSOUT01B	27-01-03-00	68.21	68.21	0.0023	0.0023	10.0	3.3
TSOUT02	27-01-02-00	3.30	3.30	0.0017	0.0017	10.0	5.0

Appendix C: List of Electronic Files

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BaSES Manual Section 7.8.2 specifies that electronic files containing the model and supporting material be attached to the MDCR. These files will be included in the final MDCR submission to the City.

Contents of DVD disc with electronic files will include:

- An InfoWorks™ file (Outfall-Calibration.IWC) containing the calibrated InfoWorks™ model with all the associated groups necessary to run the calibration storms.

- Time series plots of measured vs. predicted (simulated) flow and depth. (These are contained in the InfoWorks™ database and are viewed with the InfoWorks™ software using the meter templates and flow survey data.)

- ESRI ArcView shape files relevant to the model development including those developed/altered during the modeling portion of the sewershed study.

- An electronic copy of the Model Development and Calibration Report.

Appendix D: Calibration Results

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For each meter site, the calibration results are summarized with a time series plot and three statistical plots that compare the simulated results to the measured values. The time series plots show a time scale view of the calibration performance over the period in which the global events occurred. The results can be viewed in electronic form in the InfoWorks™ software to see greater detail for specific events.

Time series plots were created using the reporting tools of the InfoWorks™ software. The 12-month duration of the simulations was from May 2006 to May 2007; these are continuous simulations including dry and wet weather periods. One of the simulations used the CALAMAR radar rainfall data which is available for most of the global storms. The other simulation is based on the ground rain gauge data in Sliicer; which is a continuous record of rainfall with data for the entire period. The Sliicer rainfall data has a 30-minute time step and it represents a composite rainfall record for each meter basin (developed from and inverse distance squared composition of the rain gauges in the vicinity of each meter basin). Most of the larger events are calibrated using the CALAMAR radar rainfall simulation; when radar data was not made available the model simulation results are based on the ground based rain gauge data.

The statistical plots are a concise summary of the results that show the correlation for peak depth, peak flow, and volume for the wet weather events. Each statistical plot has a one-to-one line that represents perfect correlation between simulated and observed values. Upper and lower reference lines on the statistical plots show the envelope of the calibration criteria as defined in the BaSES manual. When the pipe is not surcharged, the calibration criteria for peak depth is ±4-inches. When the pipe is surcharged, the calibration criteria is +6 inches and -4 inches if the pipe diameter is less than 21-inches and +18 inches and -4 inches for pipes 21-inches in diameter and larger. Reference lines also mark the pipe crown to show surcharging when peak depth are greater than the pipe diameter.

Reference lines for the statistical plots of peak flow define the criteria of +25% and –10%. On the statistical plots of event volume the criteria is +20% and -10%. These calibration criteria are summarized in Table D.

Table D. Wet Weather Validation Criteria.

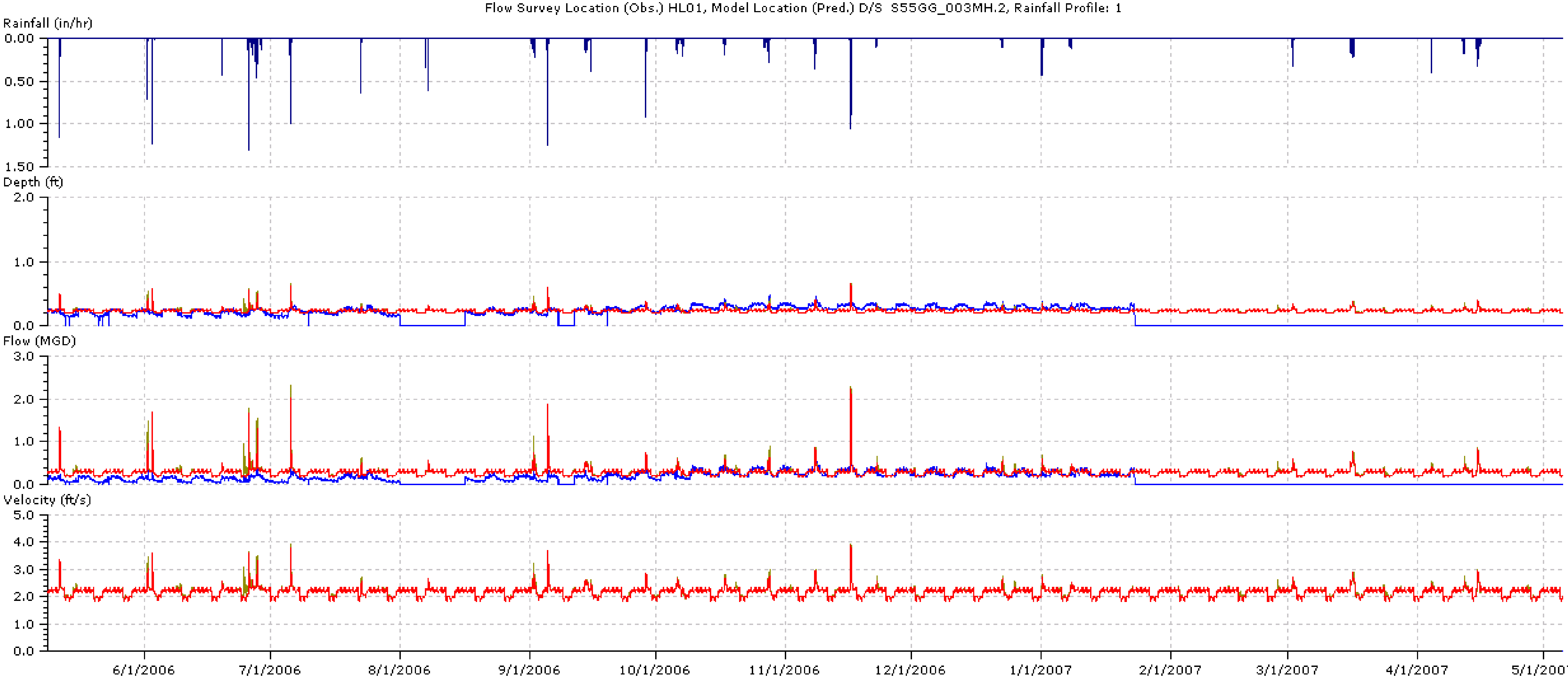
Simulated response	Percent difference from observed measurements
Peak Flow Rate	Within –10% and + 25%
Volume of Flow (assume duration from the start of rainfall to 2 days after rainfall ends)	Within –10% and + 20%
Depth of Flow in Surcharged Pipes: For pipes 21-inch diameter and larger For pipes smaller than 21-inch diameter	 Within -4 inches and +18 inches Within -4 inches and +6 inches
Depth of Flow in Unsurcharged Pipes	Within 4 inches
Shape and timing of hydrographs	Should be similar

Each statistical plot shows the data points and two regression lines that have been fitted to the data points. The solid black regression line is associated with a regression equation of the form **Ax + B**. This regression does not force the equation to pass through the origin. The equation and the goodness of fit correlation coefficient, R^2, are printed on the graph in black font.

The dotted red regression line is associated with a regression equation of the form **Ax**, which assumes a y-intercept of zero. The equation and the goodness of fit correlation coefficient, R^2, are printed on the graph in red font. The slope of the line (represented by coefficient A) is an overall indication of how close the simulated values are to the observed values. The correlation coefficient, R^2, is an indication of how well the model fits for a variety of wet weather conditions.

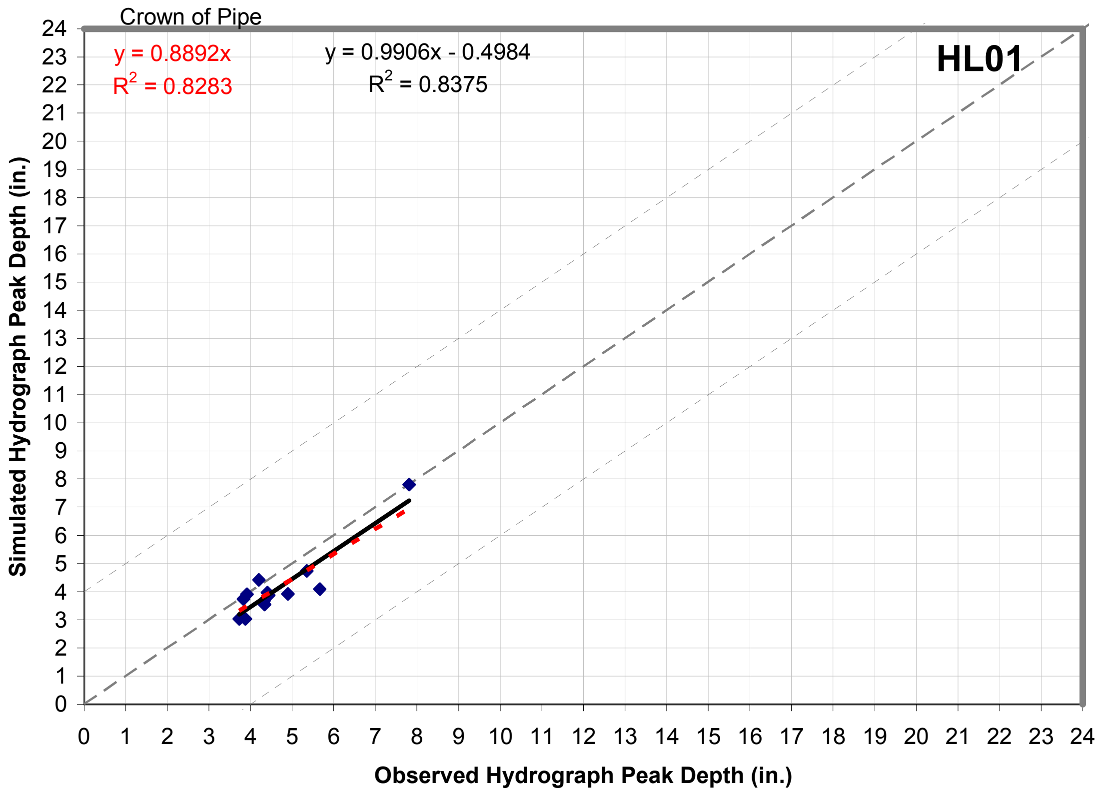
Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 1 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

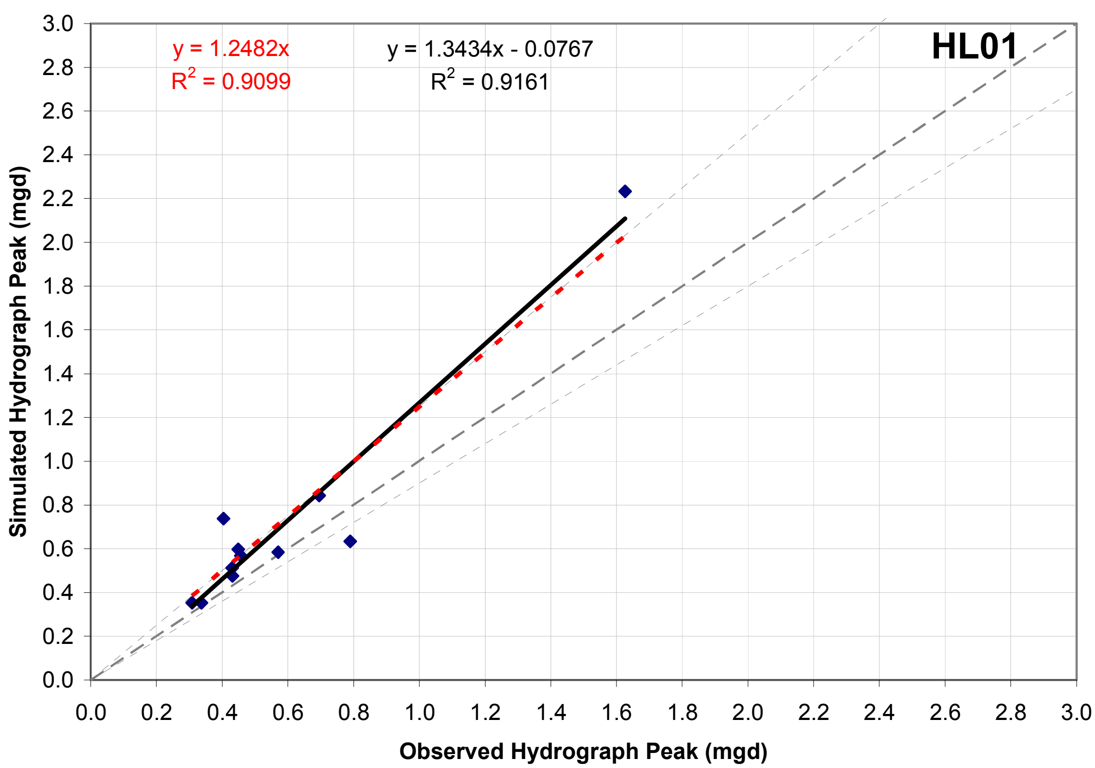
Flow Survey Location (Obs.) HL01, Model Location (Pred.) D/S S55GG_003MH.2, Rainfall Profile: 1

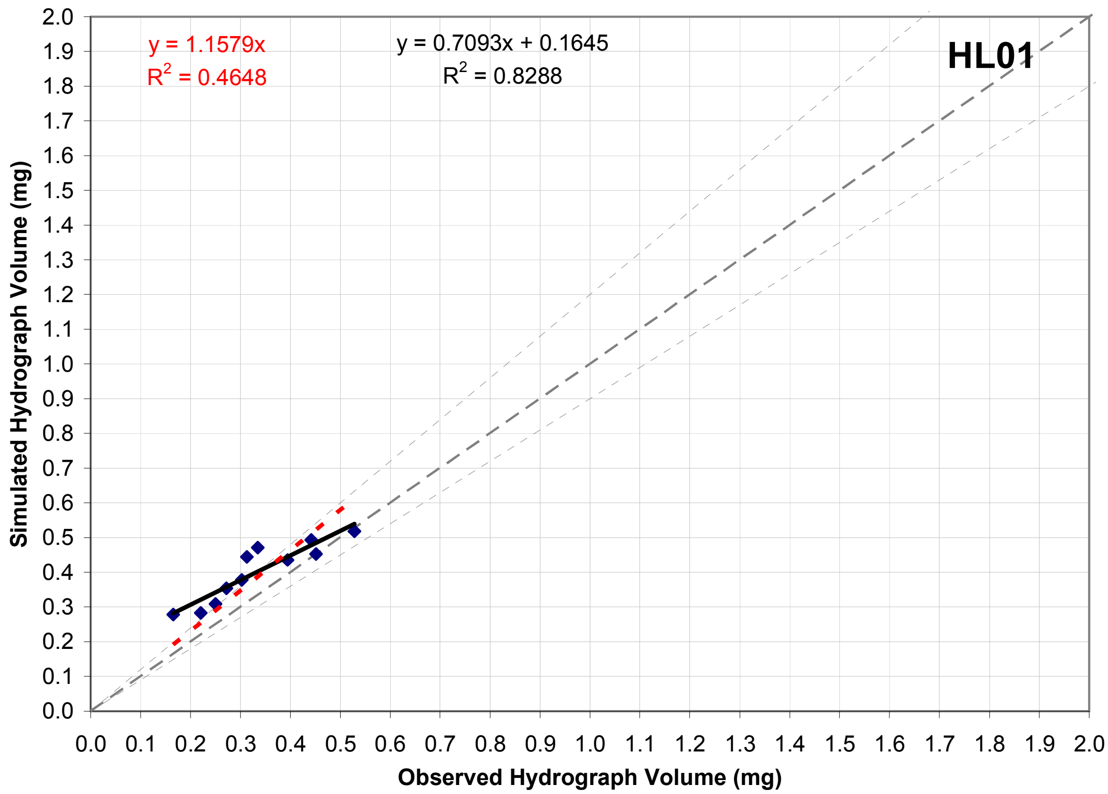


	Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
	Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain	35.515	1.304	0.004							
Obs.				0.000	0.651	0.000	1.627	47.509	0.000	0.000
...>ModelSim>A18>GaugeRain				0.191	0.663	0.182	2.309	105.002	1.835	3.931
...>ModelSim>A18>RadarRain				0.191	0.651	0.182	2.229	102.907	1.835	3.891

HL01


Crown of Pipe
y = 0.8892x
R2 = 0.8283
y = 0.9906x - 0.4984
R2 = 0.8375
HL01
Simulated Hydrograph Peak Depth (in.)
Observed Hydrograph Peak Depth (in.)


y = 1.2482x
R2 = 0.9099
y = 1.3434x - 0.0767
R2 = 0.9161
HL01
Simulated Hydrograph Peak (mgd)
Observed Hydrograph Peak (mgd)



Notes:

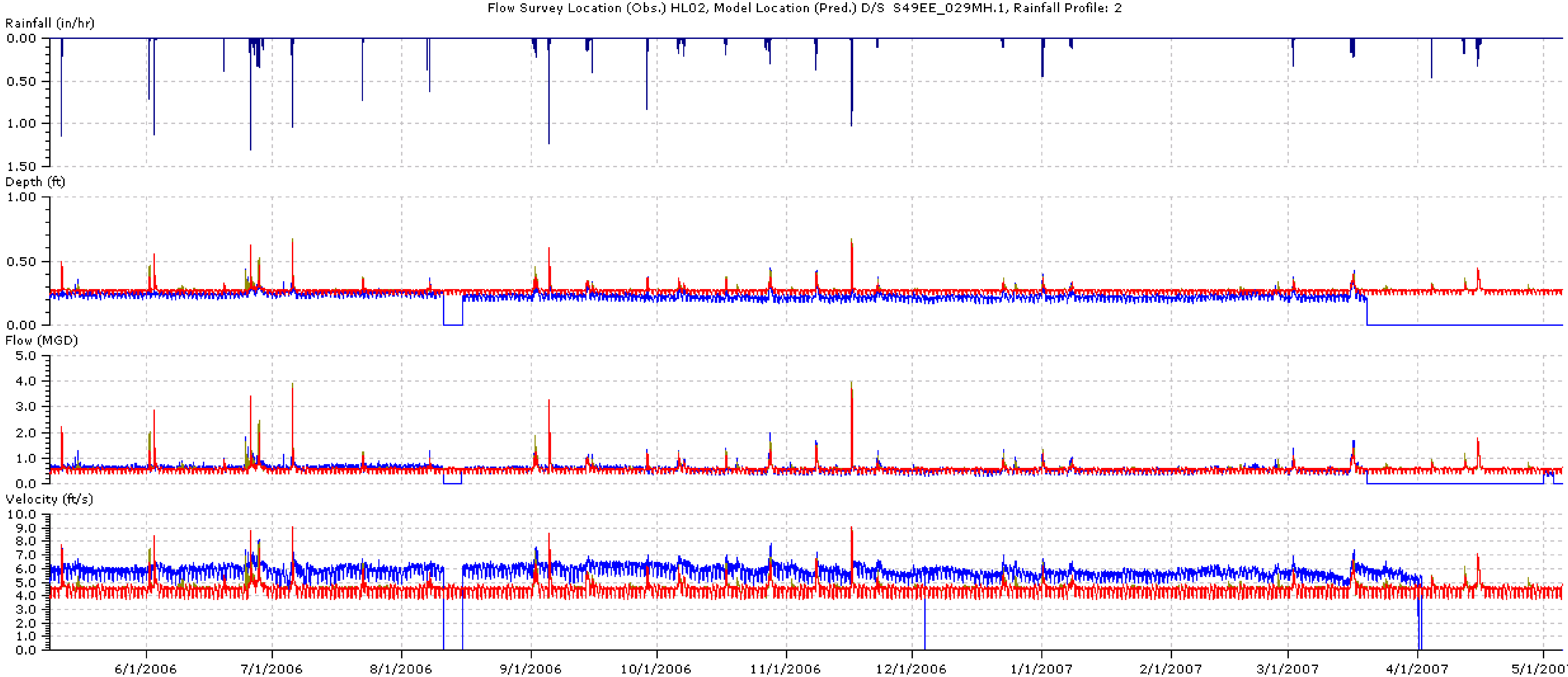
Measured velocity data in Sliicer is not hydraulically realistic.

Depth shifts upward after October 2006; therefore, events after this shift are used for calibration.

Assume measured water depth values are valid. Depth values typically 3 to 4 inches; peak depth is 8 inches which is 33% full. Depth measurements and Manning's equation were used to estimate flow rates and volumes.

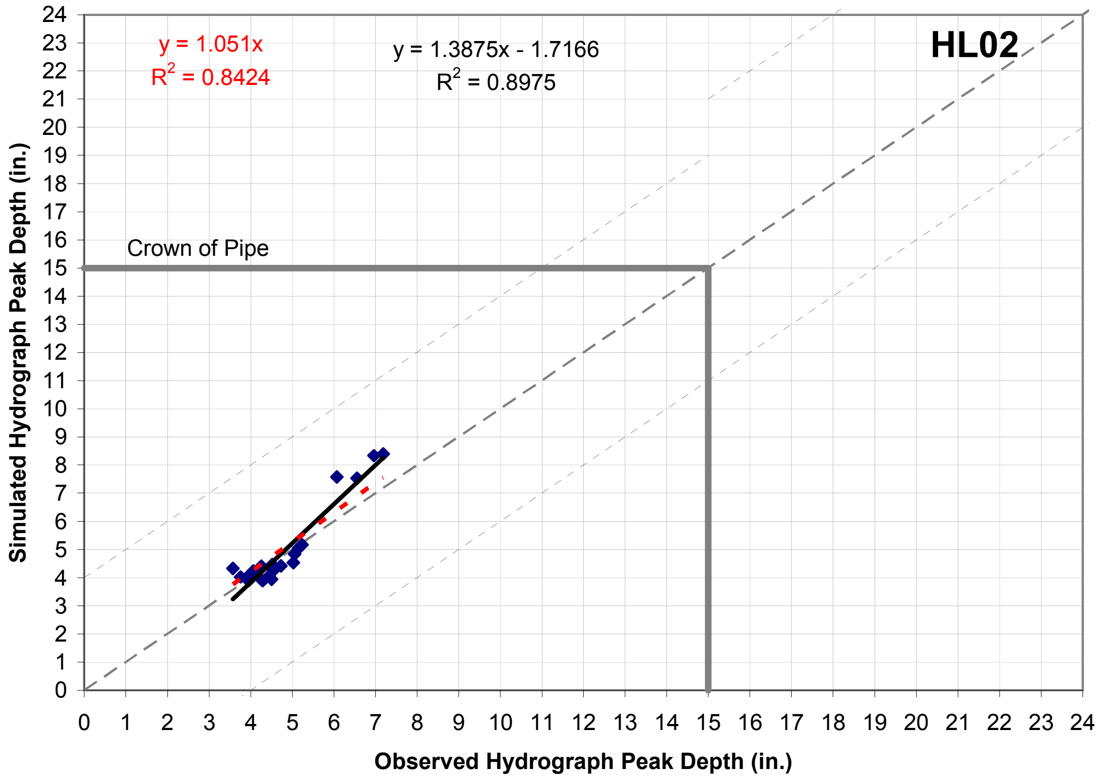
Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 2 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

Flow Survey Location (Obs.) HL02, Model Location (Pred.) D/S S49EE_029MH.1, Rainfall Profile: 2

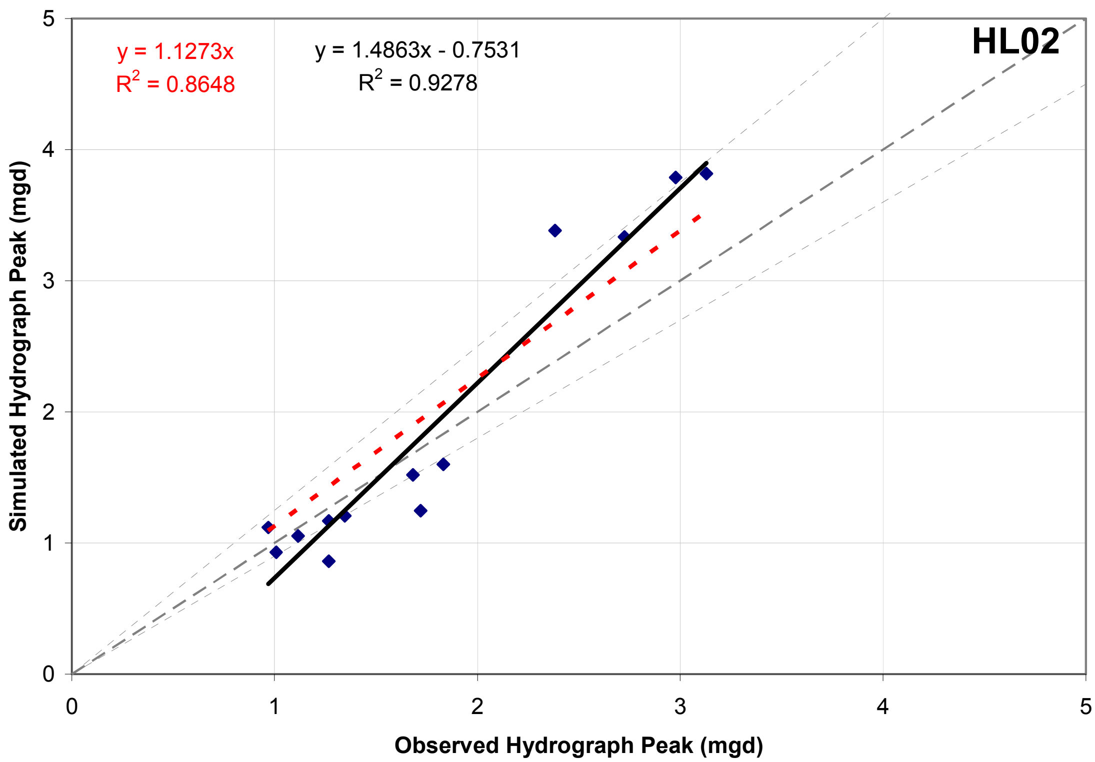


		Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
		Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain		35.668	1.300	0.004							
Obs.					0.000	0.599	0.000	3.130	180.768	0.000	8.450
...>ModelSim>A18>GaugeRain					0.239	0.677	0.401	3.971	207.229	3.779	9.086
...>ModelSim>A18>RadarRain					0.239	0.644	0.401	3.726	203.582	3.779	9.040

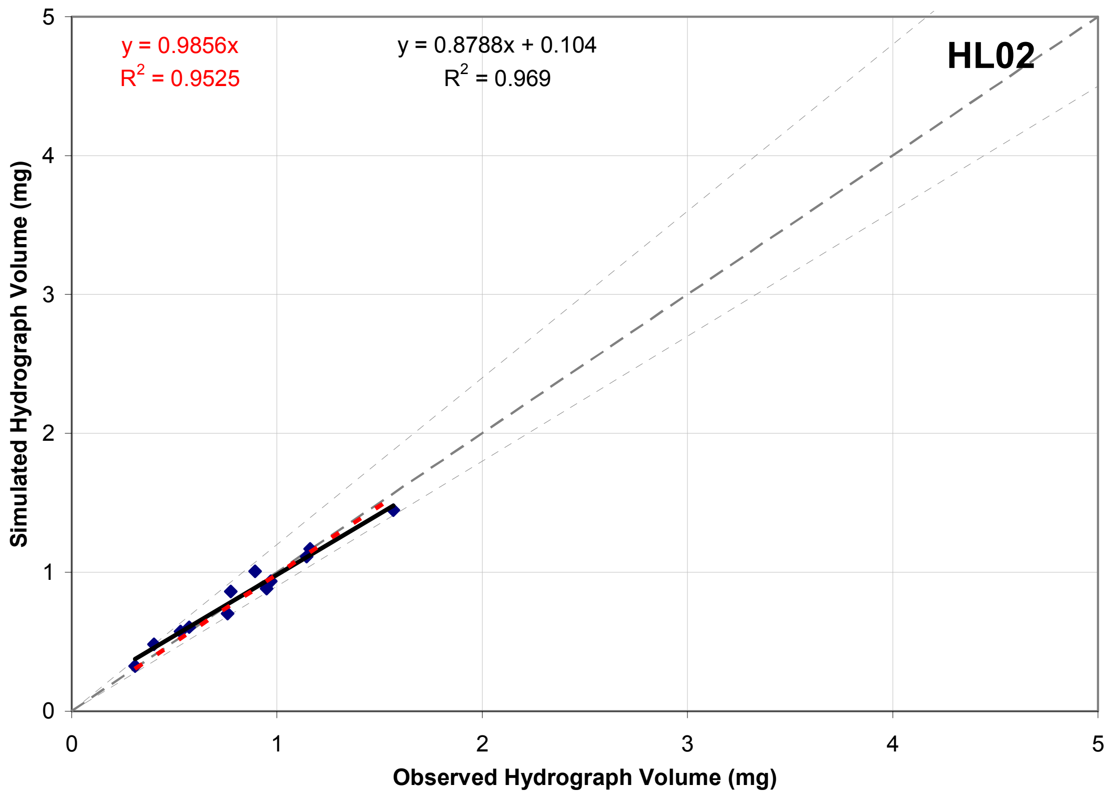
HL02



y = 1.051x
R^2 = 0.8424
y = 1.3875x - 1.7166
R^2 = 0.8975
HL02
Crown of Pipe
Simulated Hydrograph Peak Depth (in.)
Observed Hydrograph Peak Depth (in.)



y = 1.1273x
R^2 = 0.8648
y = 1.4863x - 0.7531
R^2 = 0.9278
HL02
Simulated Hydrograph Peak (mgd)
Observed Hydrograph Peak (mgd)

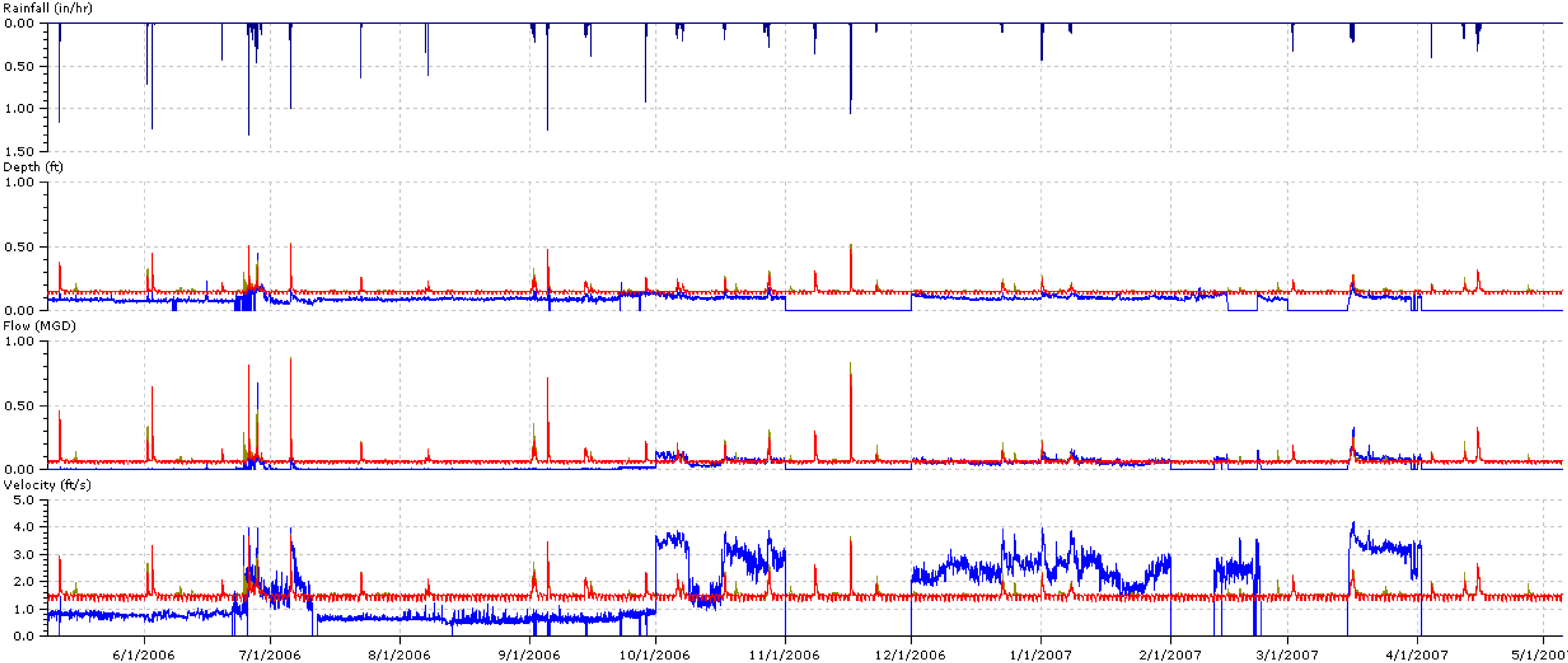


Notes:

Water depths during dry weather conditions are relatively shallow (approximately 3 inches). Measured velocities during dry weather are unusually high (5.5 to 6 feet per second); this may be due to unusually smooth conditions in the vitreous clay pipe or a measurement bias during shallow water conditions. Measured and simulated velocities match best during peak wet weather conditions when water depth is greater.

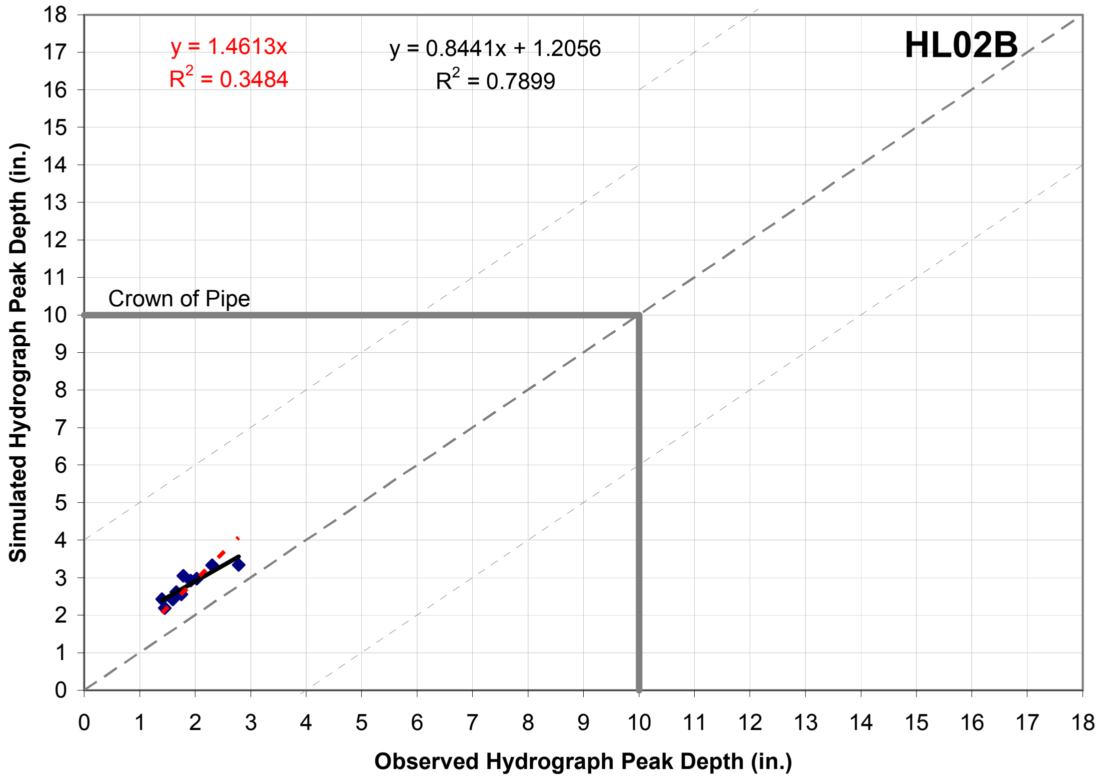
Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 3 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

Flow Survey Location (Obs.) HL02B, Model Location (Pred.) D/S S45EE_028MH.1, Rainfall Profile: 4

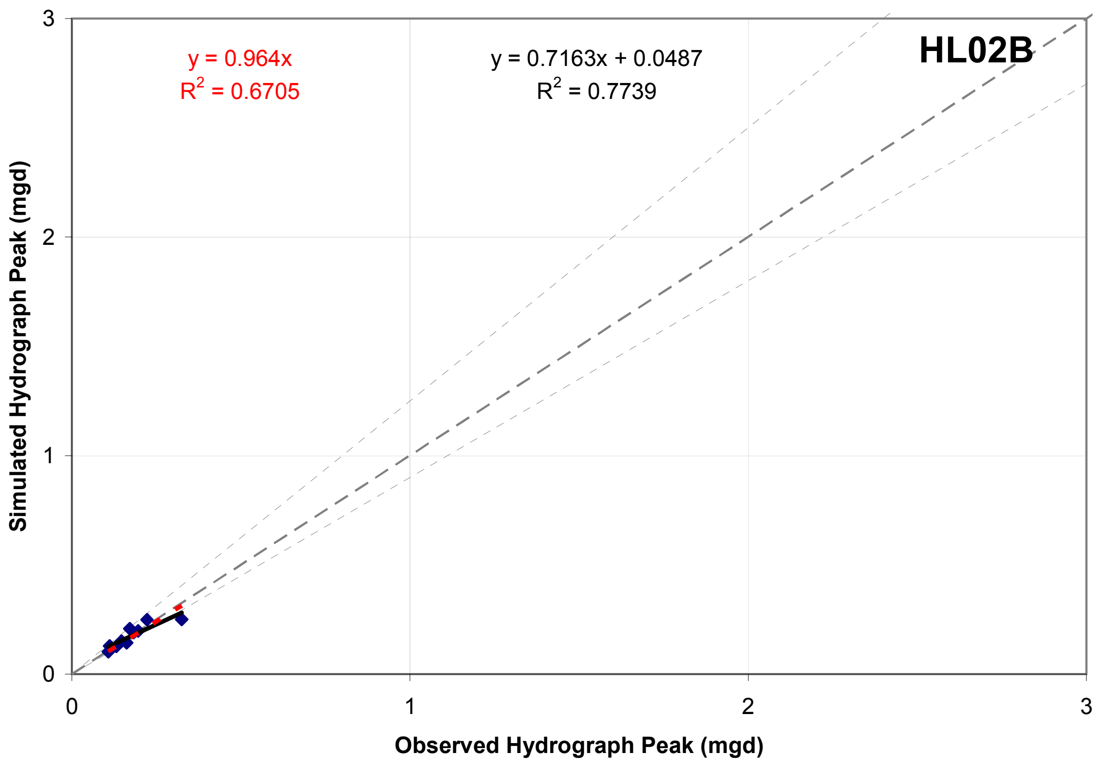


	Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
	Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain	35.515	1.304	0.004							
Obs.				0.000	0.449	0.000	0.675	8.307	0.000	4.205
...>ModelSim>A18>GaugeRain				0.129	0.525	0.044	0.874	24.121	1.279	3.741
...>ModelSim>A18>RadarRain				0.129	0.518	0.044	0.853	23.403	1.279	3.704

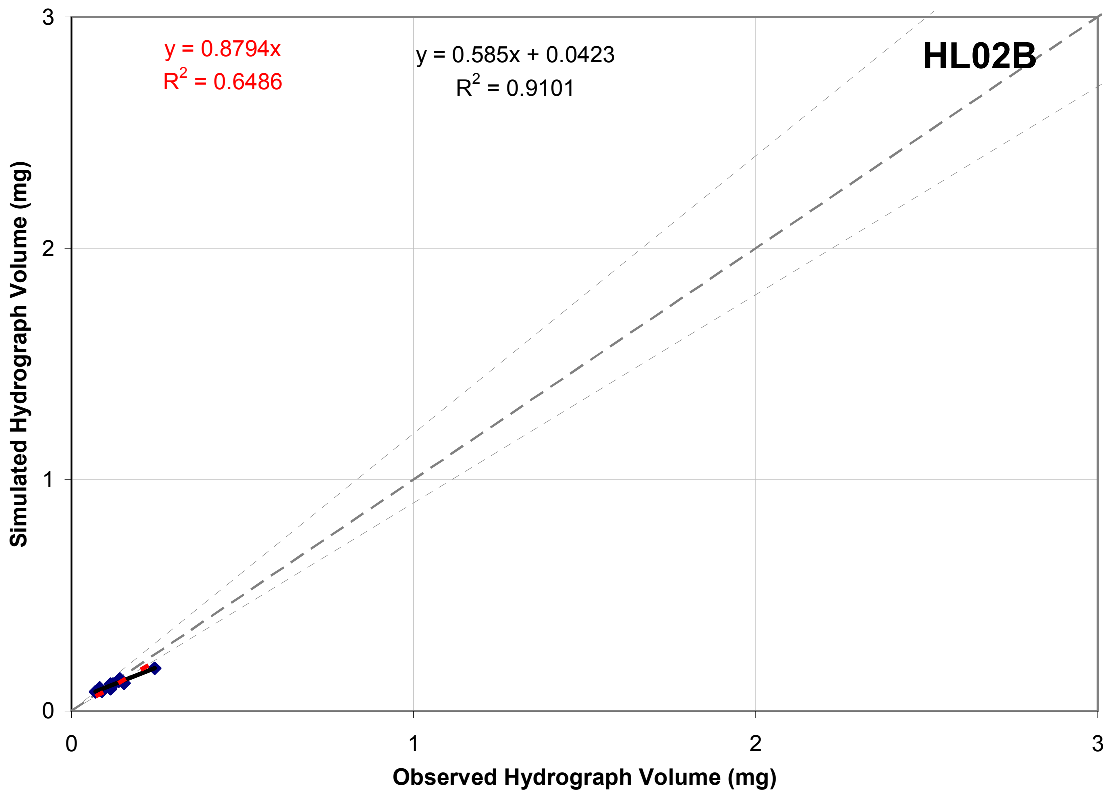
HL02B



HL02B
y = 1.4613x
R2 = 0.3484
y = 0.8441x + 1.2056
R2 = 0.7899
Crown of Pipe
Simulated Hydrograph Peak Depth (in.)
Observed Hydrograph Peak Depth (in.)



HL02B
y = 0.964x
R2 = 0.6705
y = 0.7163x + 0.0487
R2 = 0.7739
Simulated Hydrograph Peak (mgd)
Observed Hydrograph Peak (mgd)

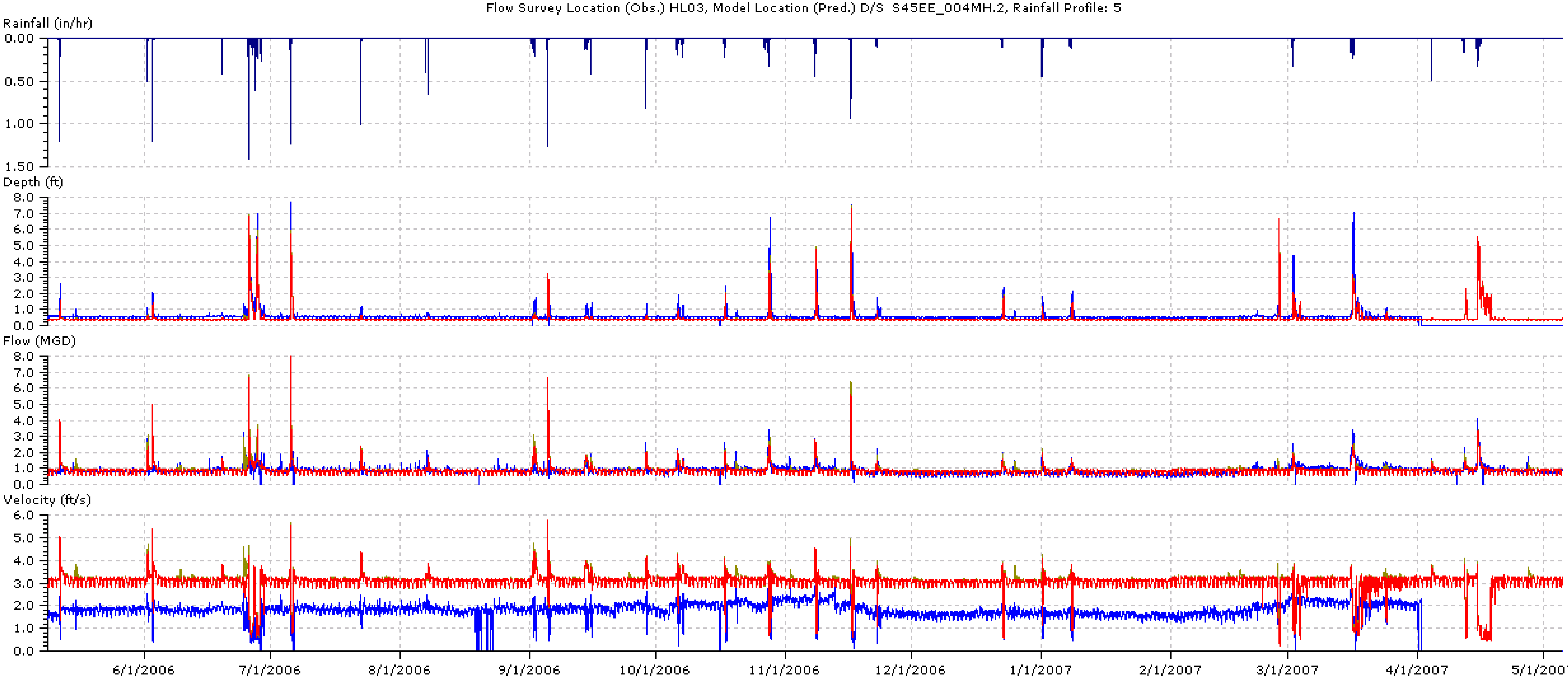


Notes:

Meter HL02B has shallow water and low velocity conditions; both of these factors increase the uncertainty and variability in the measured values. During peak flow conditions the depth is approximately 3 inches (30% full).

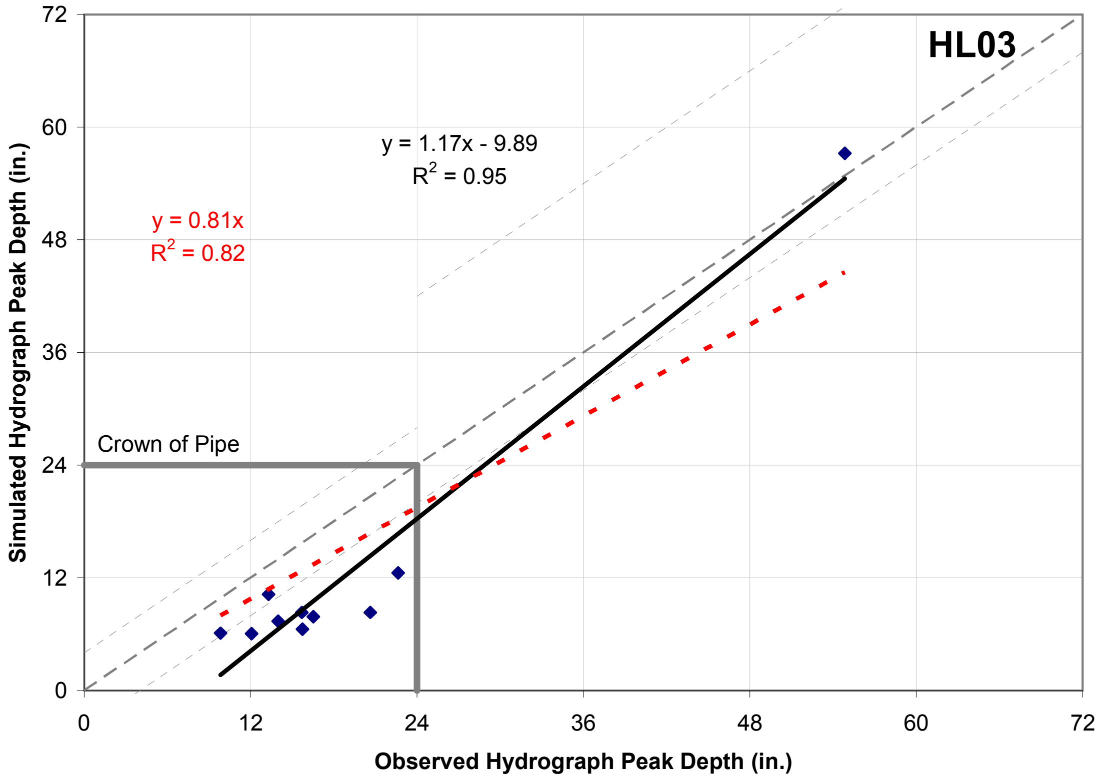
Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 4 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

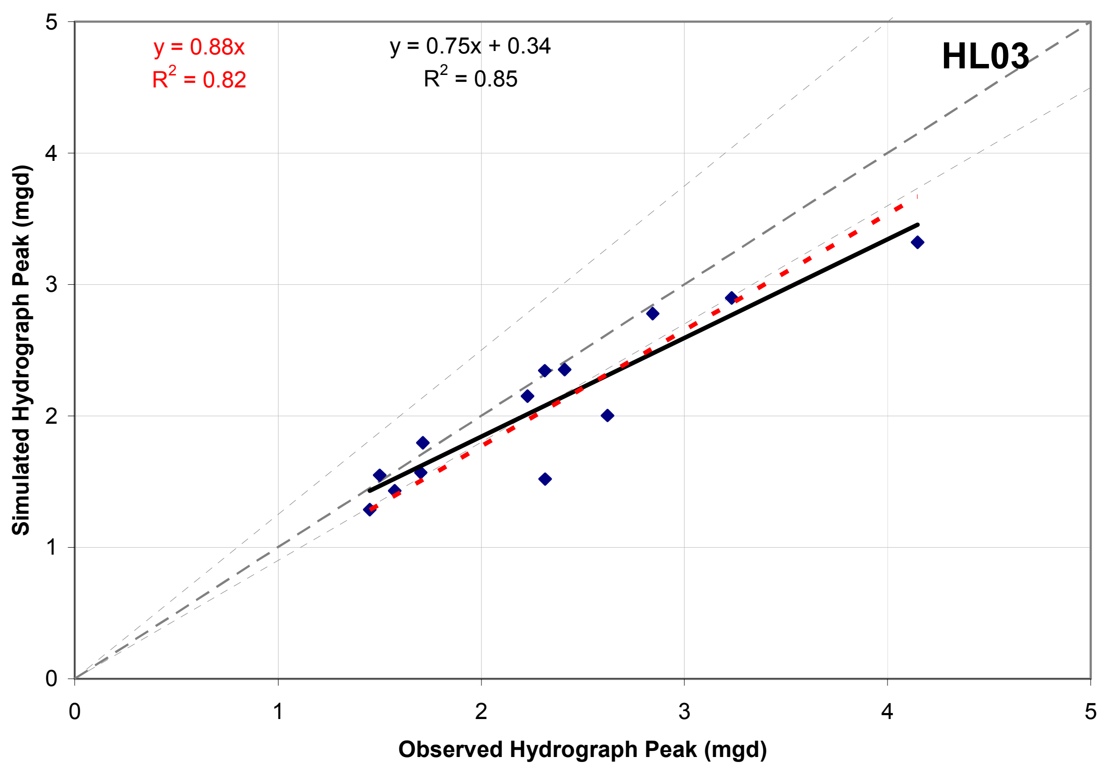
Flow Survey Location (Obs.) HL03, Model Location (Pred.) D/S S45EE_004MH.2, Rainfall Profile: 5

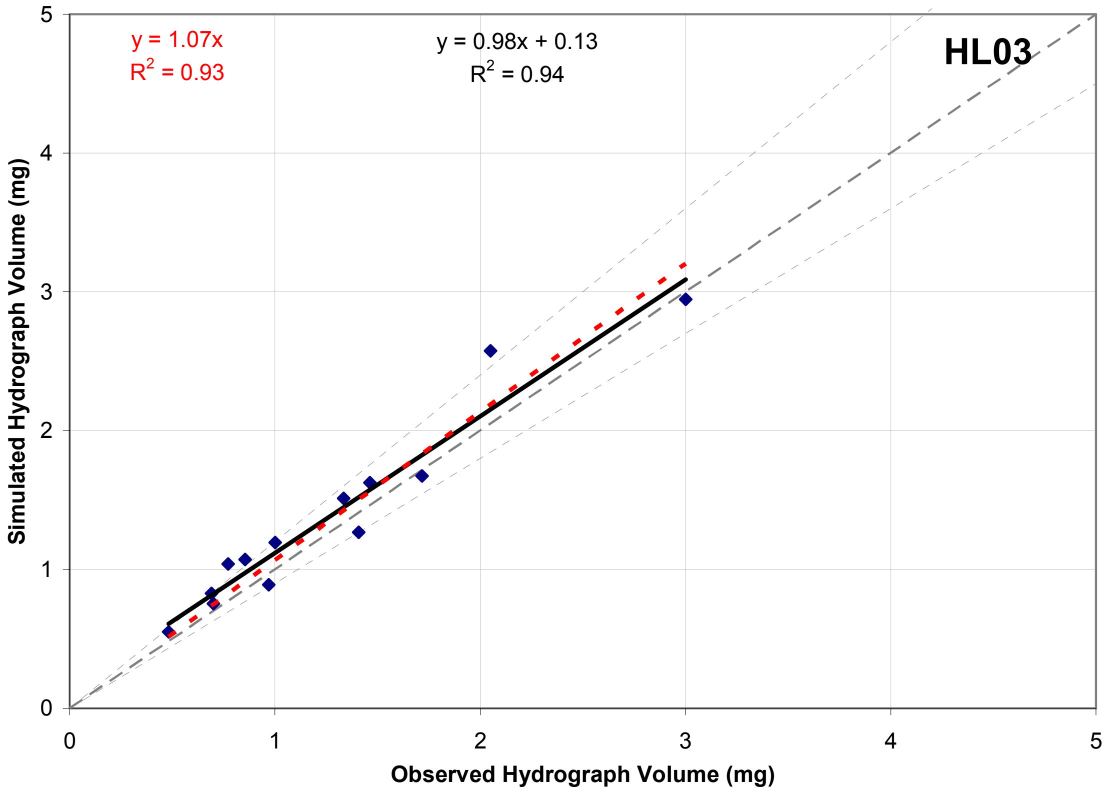


	Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
	Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain	36.843	1.414	0.004							
Obs.				0.000	7.659	0.000	5.180	303.973	0.000	3.025
...>ModelSim>A18>GaugeRain				0.295	7.443	0.530	7.979	320.476	0.317	5.657
...>ModelSim>A18>RadarRain				0.295	7.323	0.529	8.094	312.284	0.252	5.753

HL03


HL03
y = 1.17x - 9.89
R^2 = 0.95
y = 0.81x
R^2 = 0.82
Crown of Pipe
Simulated Hydrograph Peak Depth (in.)
Observed Hydrograph Peak Depth (in.)
0
12
24
36
48
60
72


HL03
y = 0.88x
R^2 = 0.82
y = 0.75x + 0.34
R^2 = 0.85
Simulated Hydrograph Peak (mgd)
Observed Hydrograph Peak (mgd)
0
1
2
3
4
5

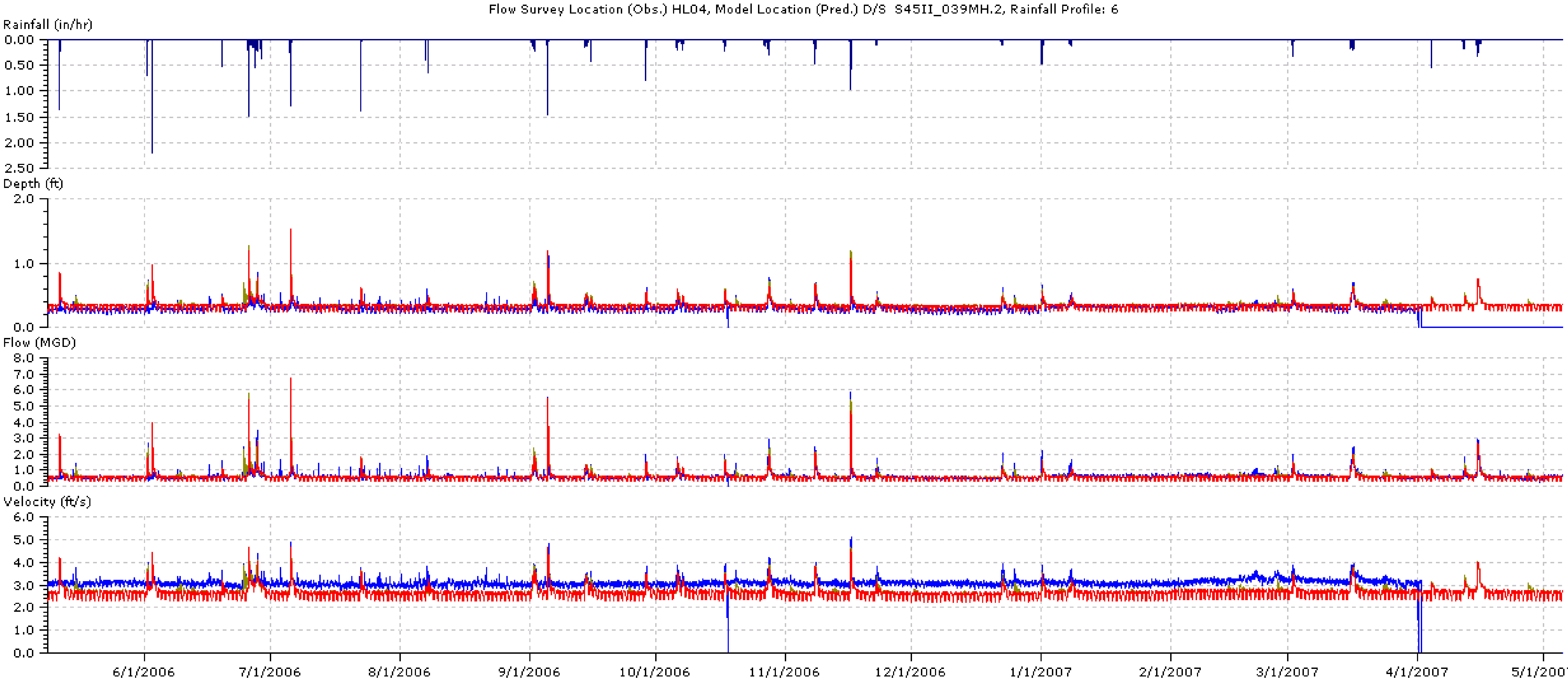


Note:

Meter HL03 is located at the downstream end of the branch that has meters HL04 and HL05 further upstream. In general there is a steady increase in flow from upstream at HL05 to downstream at HL03.

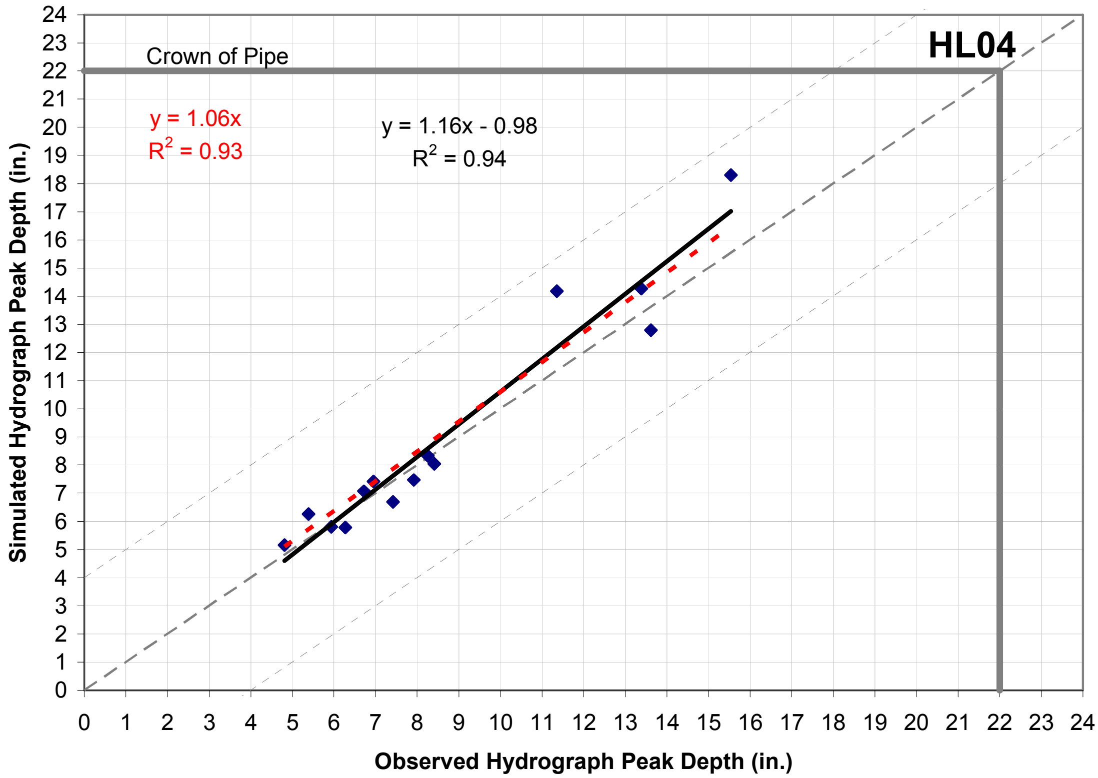
Measured water depth values at HL03 show surcharging at the meter due to high water levels in the Outfall sewer. During surcharge events, the measured depths increase and the velocities decrease. For some events the recorded peak flow rate values are unrealistically low (compared to the peak flow at neighboring meter HL04). Very low velocities at the sensor during surcharge events are the cause of under-reporting the peak flow rates. These events have been removed from the statistical analysis of peak flow and volume.

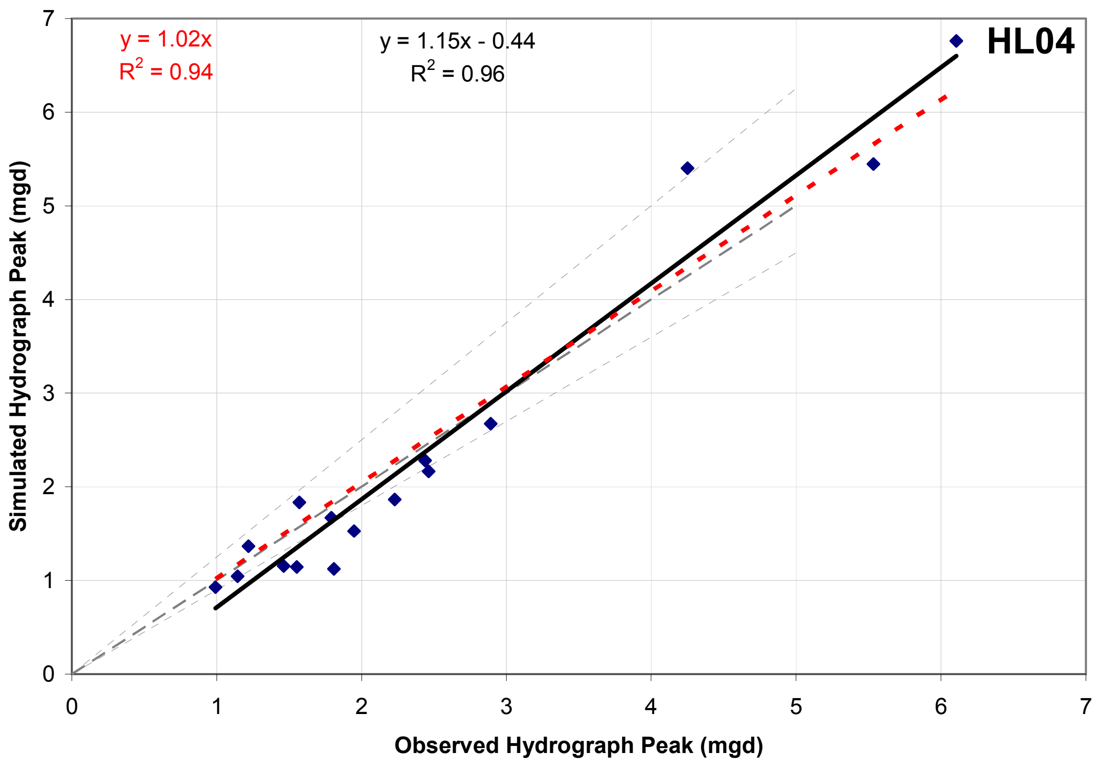
Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 5 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

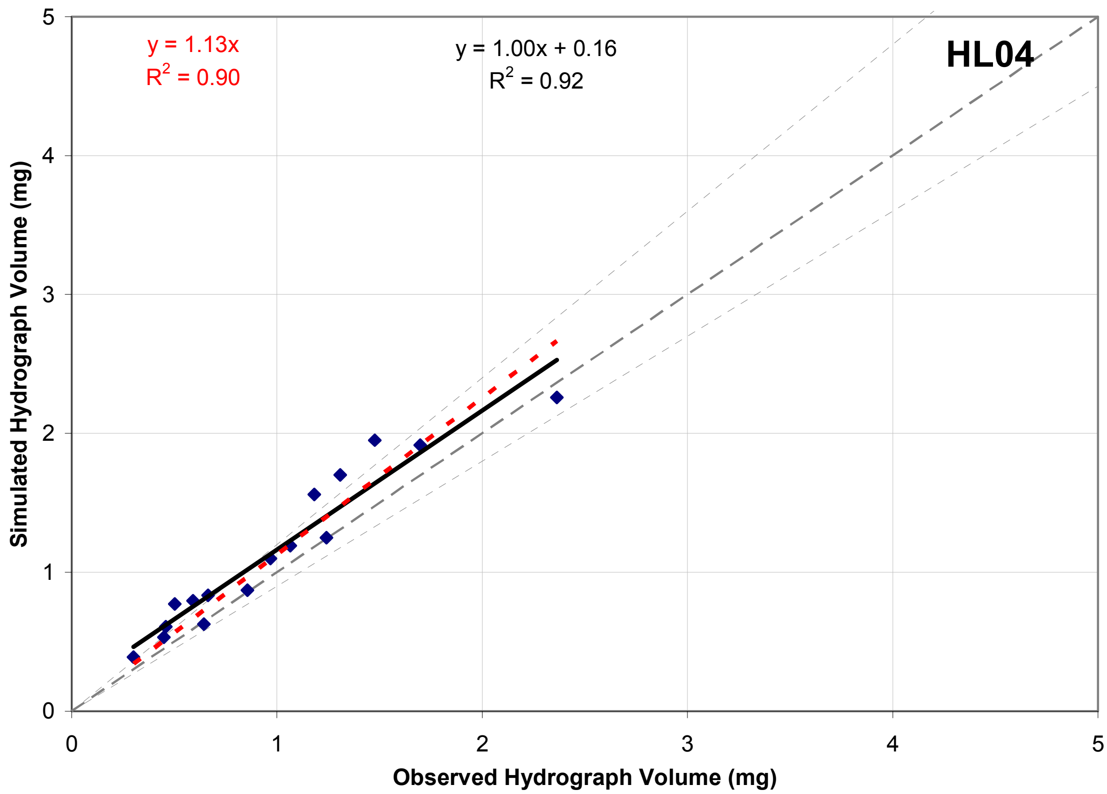


	Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
	Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain	38.446	2.194	0.004							
Obs.				0.000	1.295	0.000	6.106	212.074	0.000	5.093
...>ModelSim>A18>GaugeRain				0.240	1.469	0.298	6.666	215.651	2.264	4.660
...>ModelSim>A18>RadarRain				0.240	1.525	0.297	6.762	208.466	2.262	4.651

HL04


HL04
Crown of Pipe
y = 1.06x
R^2 = 0.93
y = 1.16x - 0.98
R^2 = 0.94
Simulated Hydrograph Peak Depth (in.)
Observed Hydrograph Peak Depth (in.)


HL04
y = 1.02x
R^2 = 0.94
y = 1.15x - 0.44
R^2 = 0.96
Simulated Hydrograph Peak (mgd)
Observed Hydrograph Peak (mgd)

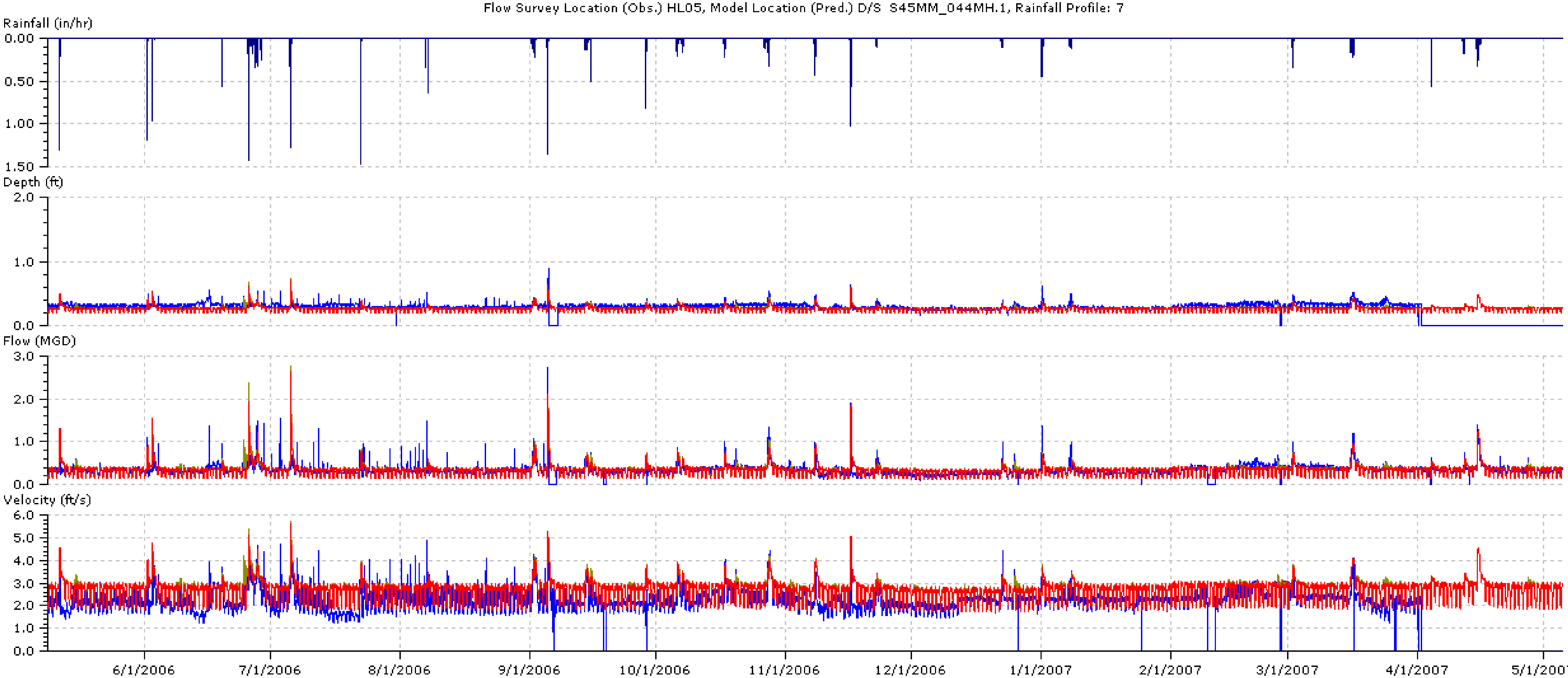


Notes:

Measured and simulated velocities match best during peak wet weather conditions when water depth is greater. Measured velocities during dry weather are higher than simulated velocities; this may be due to unusually smooth conditions in the vitreous clay pipe or a measurement bias during shallow water conditions.

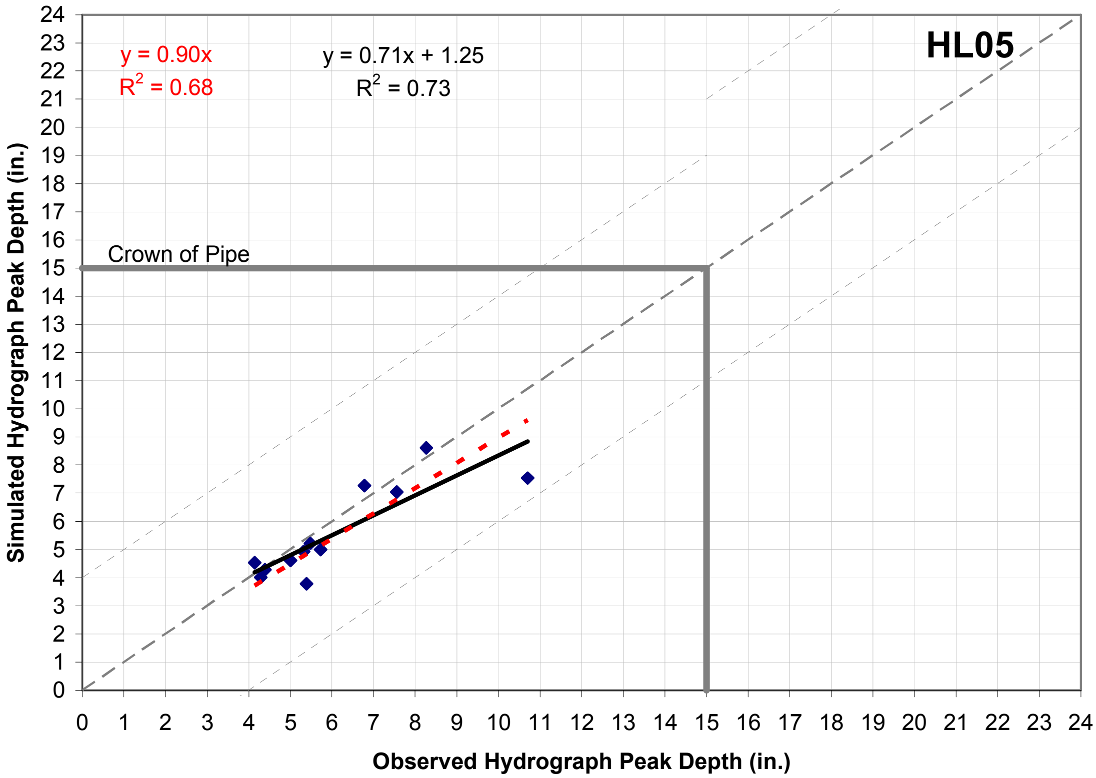
Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 6 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

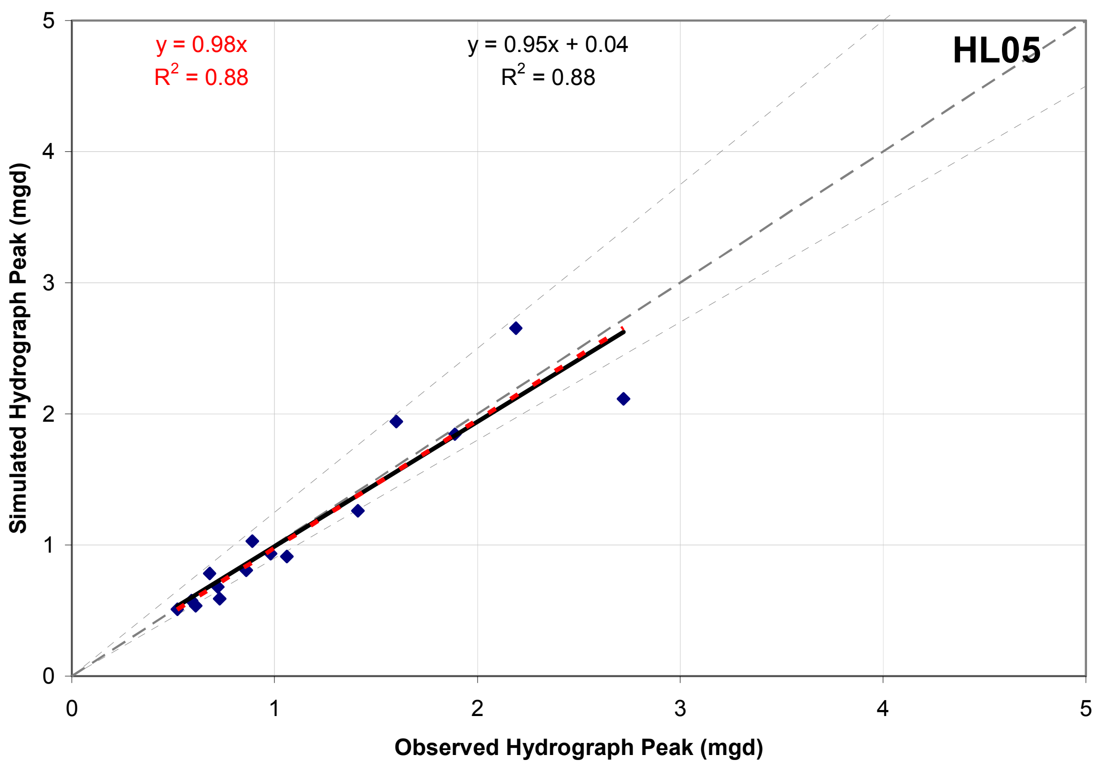
Flow Survey Location (Obs.) HL05, Model Location (Pred.) D/S S45MM_044MH.1, Rainfall Profile: 7

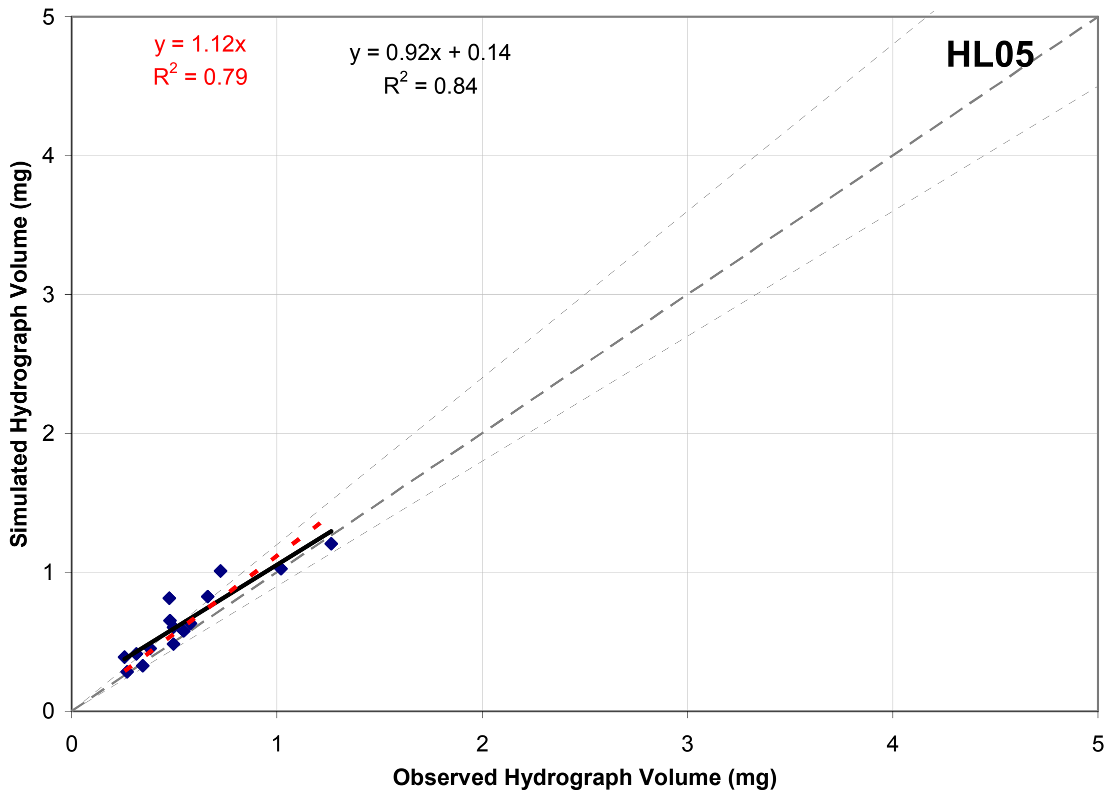


	Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
	Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain	38.152	1.474	0.004							
Obs.				0.000	0.892	0.000	2.720	117.815	0.000	4.883
...>ModelSim>A18>GaugeRain				0.190	0.732	0.131	2.753	122.799	1.726	5.708
...>ModelSim>A18>RadarRain				0.190	0.718	0.131	2.652	119.178	1.723	5.626

HL05


HL05
y = 0.90x
R^2 = 0.68
y = 0.71x + 1.25
R^2 = 0.73
Crown of Pipe
Simulated Hydrograph Peak Depth (in.)
Observed Hydrograph Peak Depth (in.)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24


HL05
y = 0.98x
R^2 = 0.88
y = 0.95x + 0.04
R^2 = 0.88
Simulated Hydrograph Peak (mgd)
Observed Hydrograph Peak (mgd)
0 1 2 3 4 5



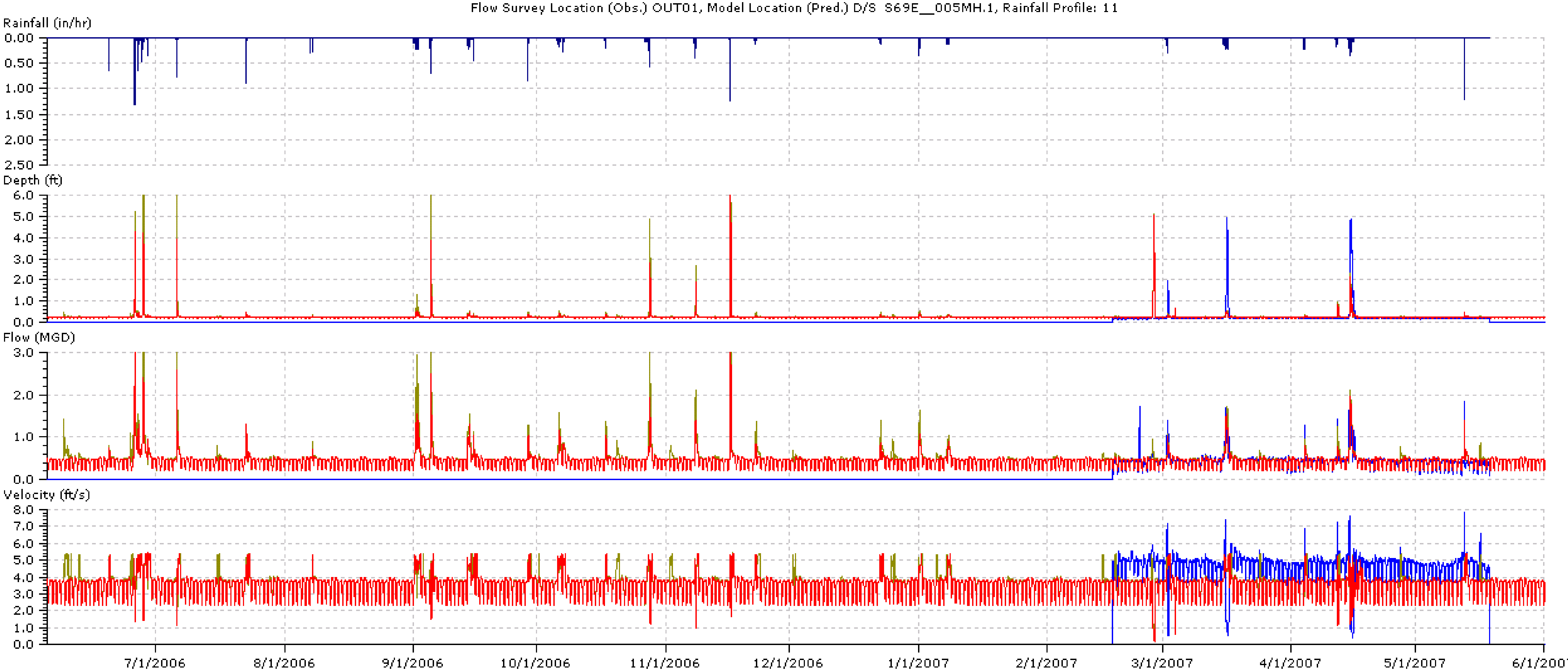
Notes:

Meter HL05 is located in the 15-inch pipe flowing into manhole S45MM_036MH (N. Duncan and E. 20th St Alley). At this manhole the direction of flow turns sharply to the left (from East to South); therefore, it is not possible to develop uniform flow conditions at the meter site.

The measured flow data show that the peak flows are near critical flow conditions (Froude number approximately equal to 1). Under these conditions, the water surface is less stable and typically has irregular wave patterns.

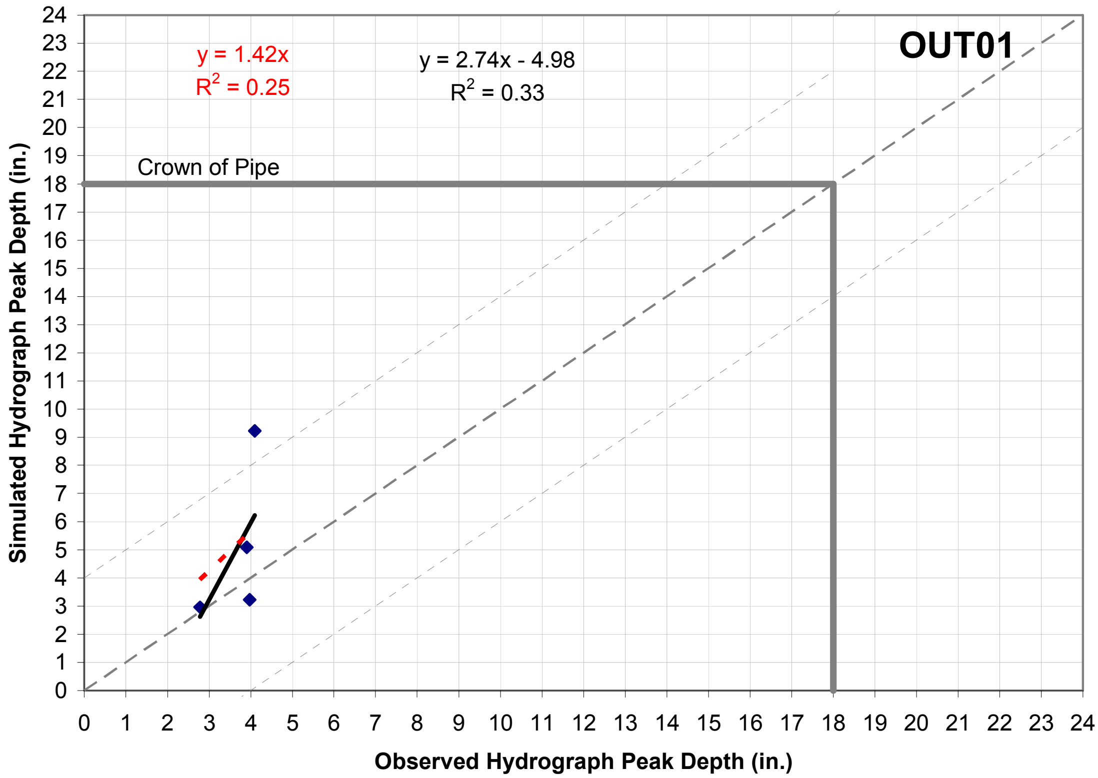
Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 8 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

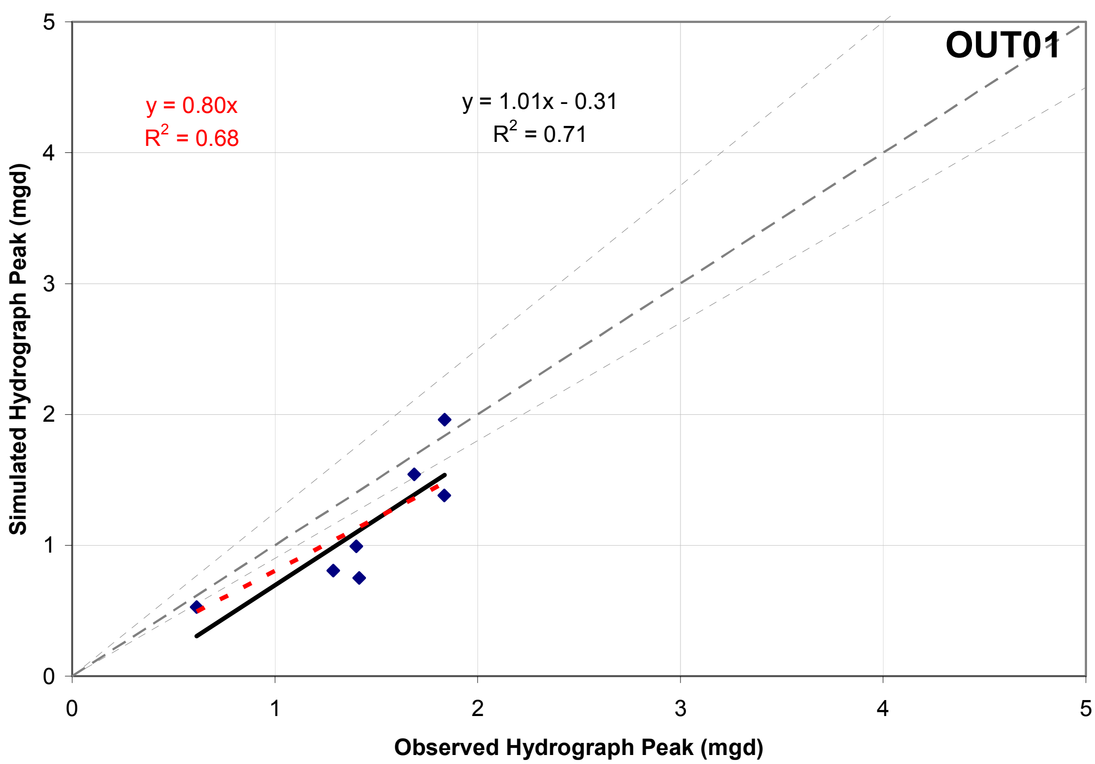
Flow Survey Location (Obs.) OUT01, Model Location (Pred.) D/S S69E__005MH.1, Rainfall Profile: 11

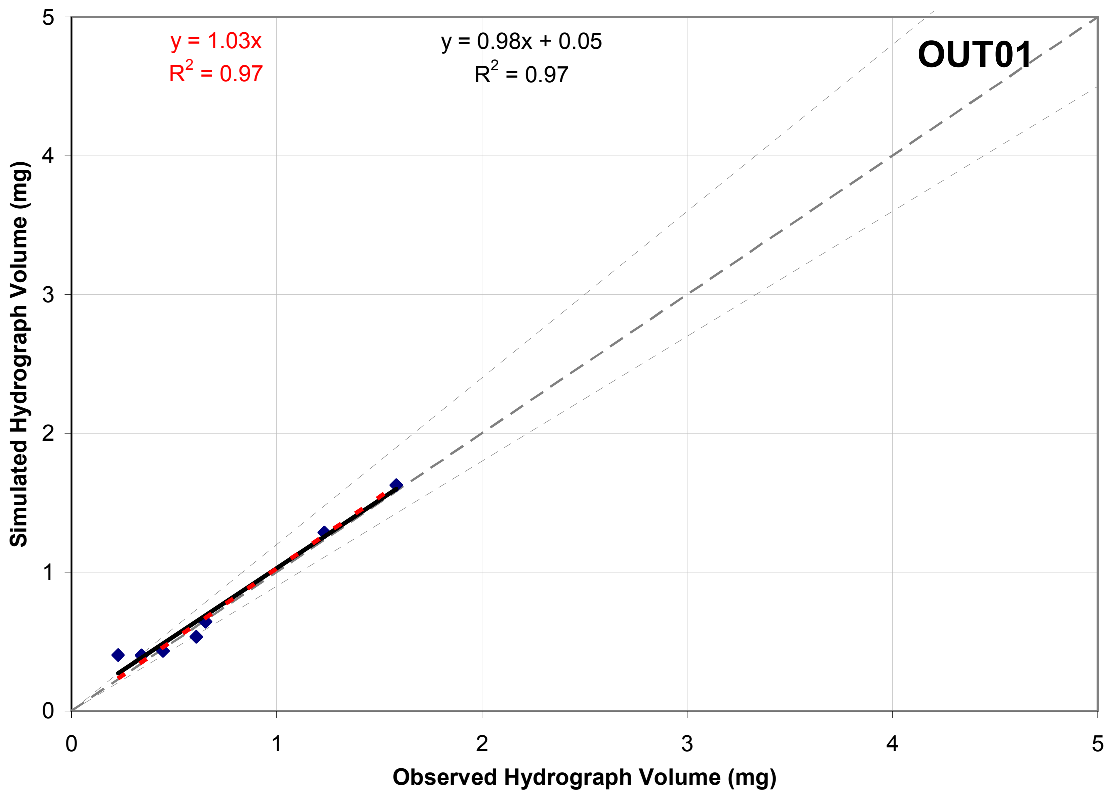


	Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
	Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain	33.476	1.310	0.004							
Obs.				0.000	4.921	0.000	1.837	38.493	0.000	7.826
...>ModelSim>A18>GaugeRain				0.176	11.477	0.212	6.459	168.919	0.252	5.421
...>ModelSim>A18>RadarRain				0.175	8.278	0.212	4.444	159.844	0.179	5.421

OUT01


OUT01
y = 1.42x
R^2 = 0.25
y = 2.74x - 4.98
R^2 = 0.33
Crown of Pipe
Simulated Hydrograph Peak Depth (in.)
Observed Hydrograph Peak Depth (in.)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24


OUT01
y = 0.80x
R^2 = 0.68
y = 1.01x - 0.31
R^2 = 0.71
Simulated Hydrograph Peak (mgd)
Observed Hydrograph Peak (mgd)
0
1
2
3
4
5



Note:

Monitoring data is available for meter OUTO1 from February 2007 to May 2007; therefore, six of the standard calibration events were monitored. In addition, the event on 5/12/2007 (which is not a global storm) was included in the calibration.

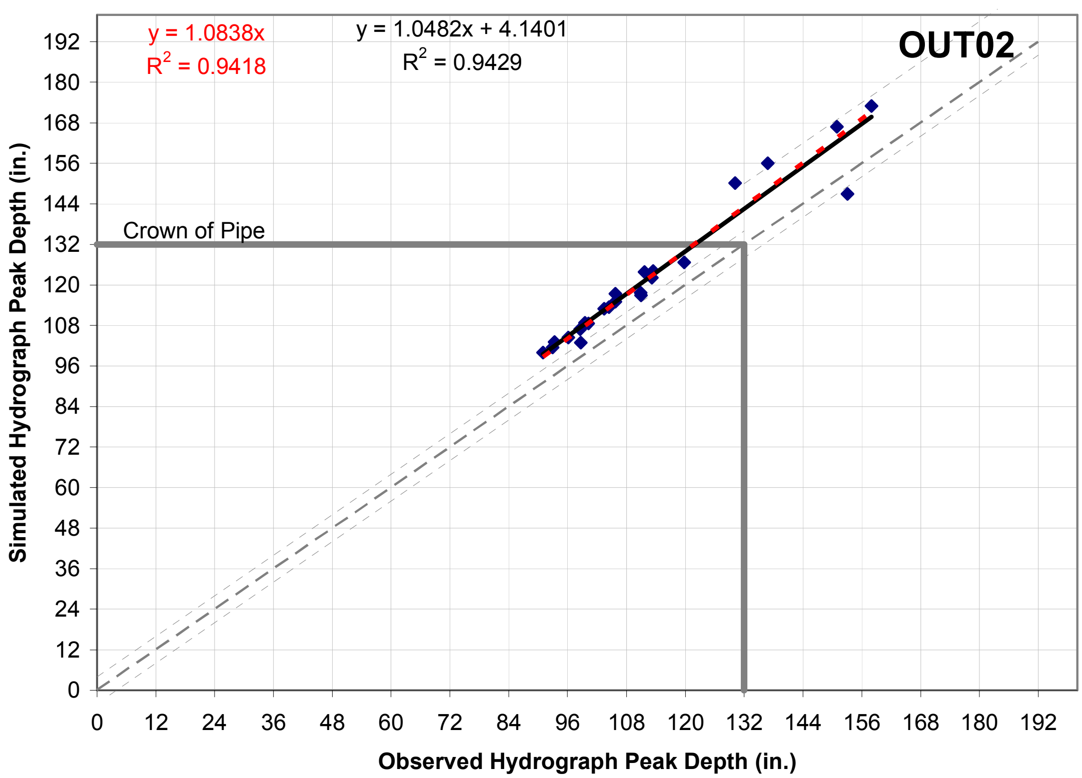
Meter OUT01 is located on the 18-inch branch sewer that connects to the Outfall Sewer near the Baltimore County line. High water levels in the Outfall Sewer cause surcharging at OUT01 during peak flow conditions.

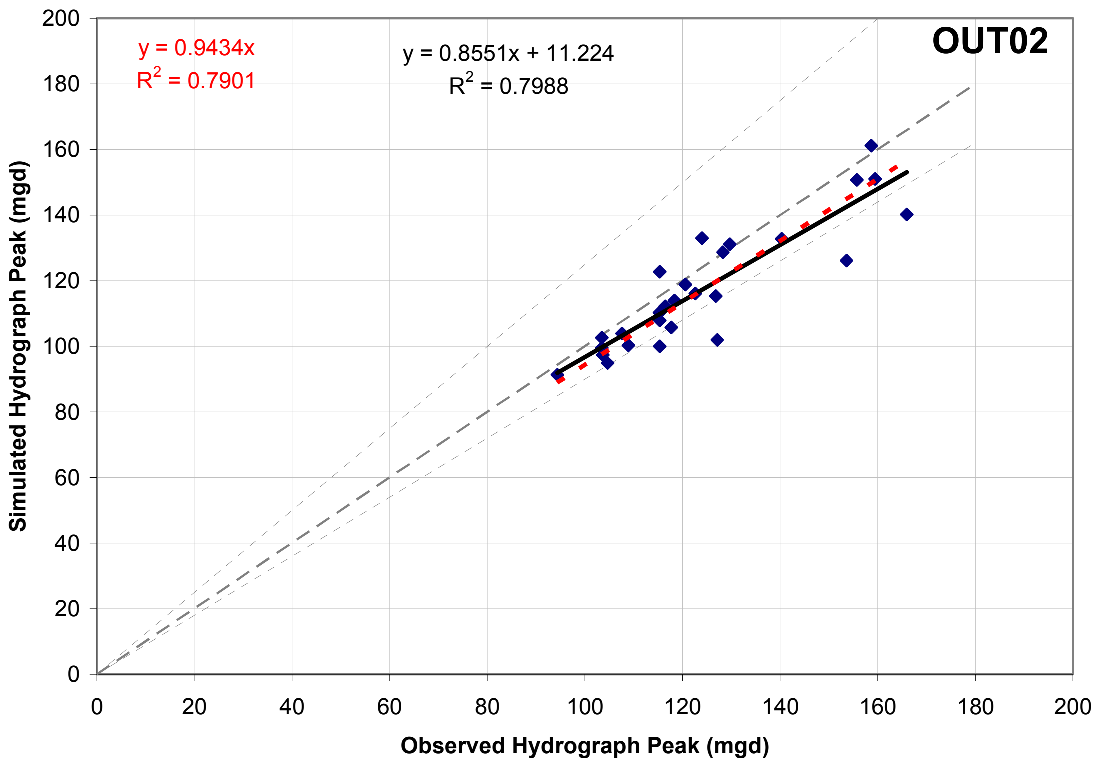
Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 9 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

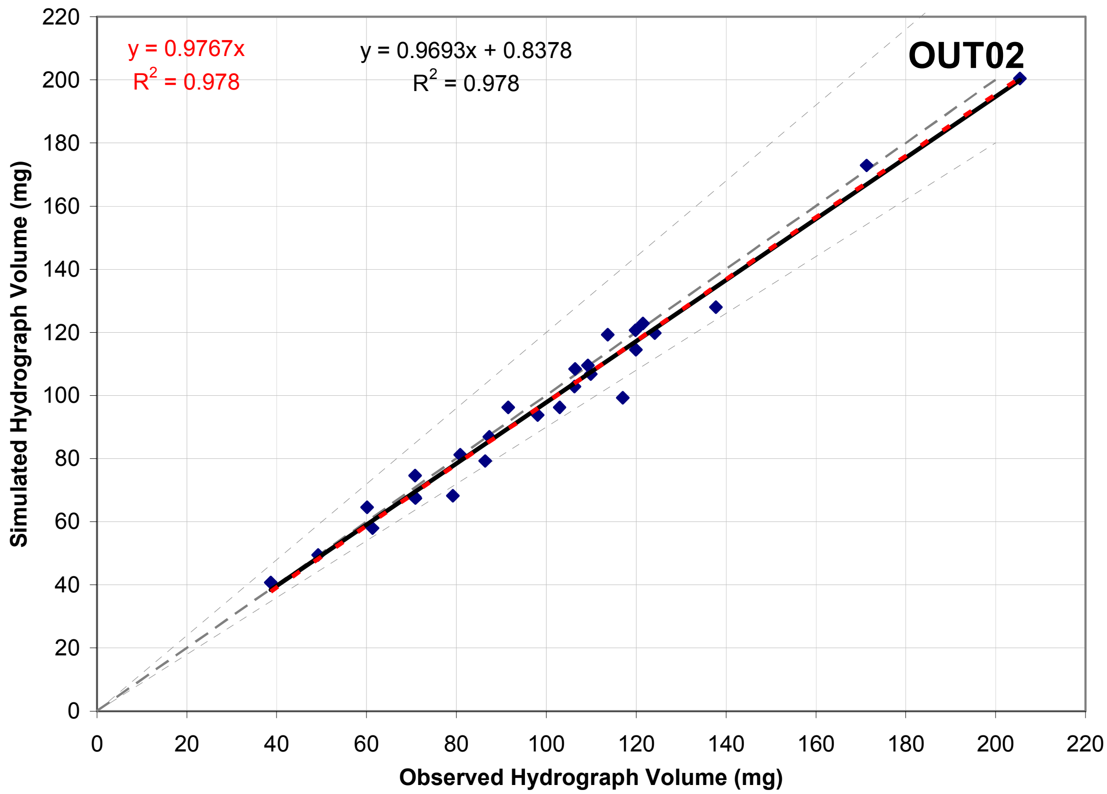
Flow Survey Location (Obs.) OUT02, Model Location (Pred.) D/S S65A__010MH.1, Rainfall Profile: 12

	Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
	Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain	36.339	1.404	0.004							
Obs.				0.000	13.166	0.000	165.961	28364.270	0.000	2.727
...>ModelSim>A18>GaugeRain				6.045	15.616	-61.361	161.210	28842.395	-1.057	2.805
...>ModelSim>A18>RadarRain				6.044	15.609	-61.367	160.786	28784.498	-1.057	2.804

OUT02

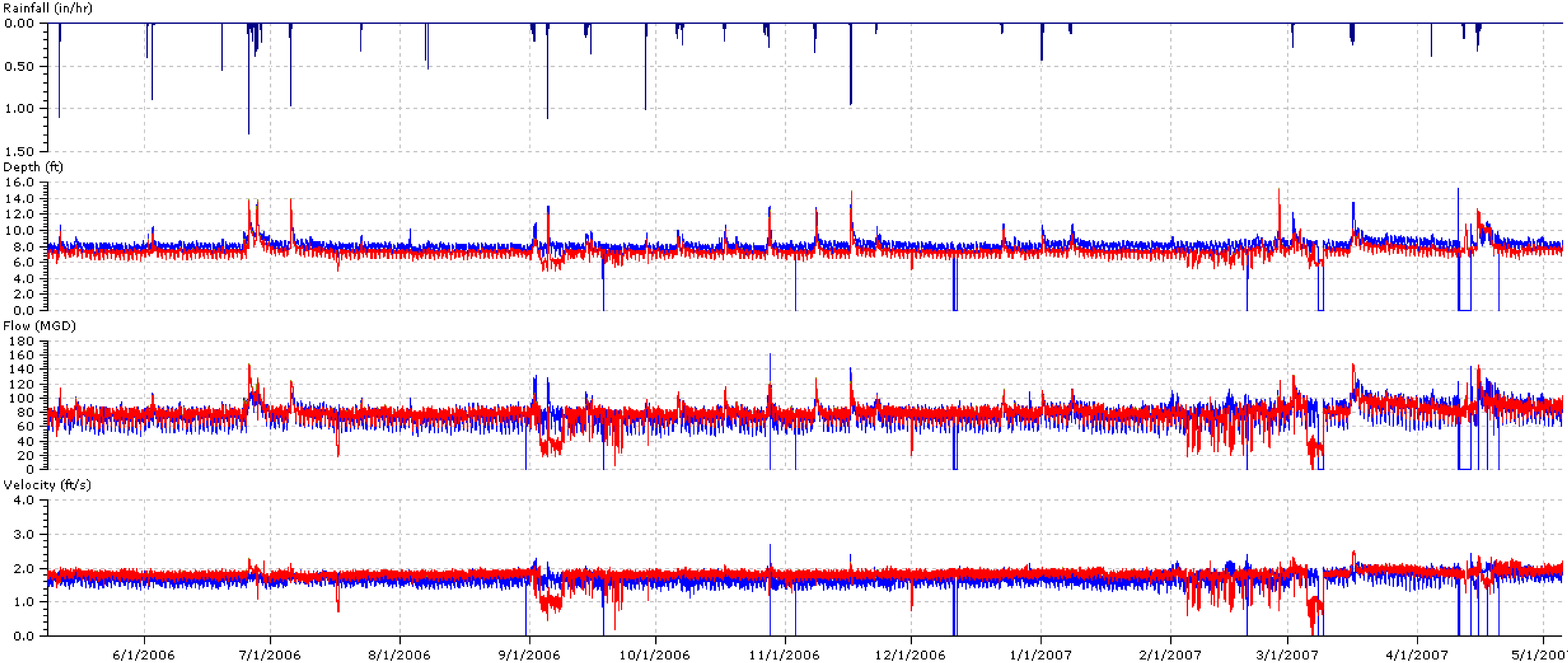

y = 1.0838x
R2 = 0.9418
y = 1.0482x + 4.1401
R2 = 0.9429
OUT02
Crown of Pipe
Simulated Hydrograph Peak Depth (in.)
Observed Hydrograph Peak Depth (in.)
0
12
24
36
48
60
72
84
96
108
120
132
144
156
168
180
192


y = 0.9434x
R2 = 0.7901
y = 0.8551x + 11.224
R2 = 0.7988
OUT02
Simulated Hydrograph Peak (mgd)
Observed Hydrograph Peak (mgd)
0
20
40
60
80
100
120
140
160
180
200


y = 0.9767x
R^2 = 0.978
y = 0.9693x + 0.8378
R^2 = 0.978
OUT02
Simulated Hydrograph Volume (mg)
Observed Hydrograph Volume (mg)
0
20
40
60
80
100
120
140
160
180
200
220

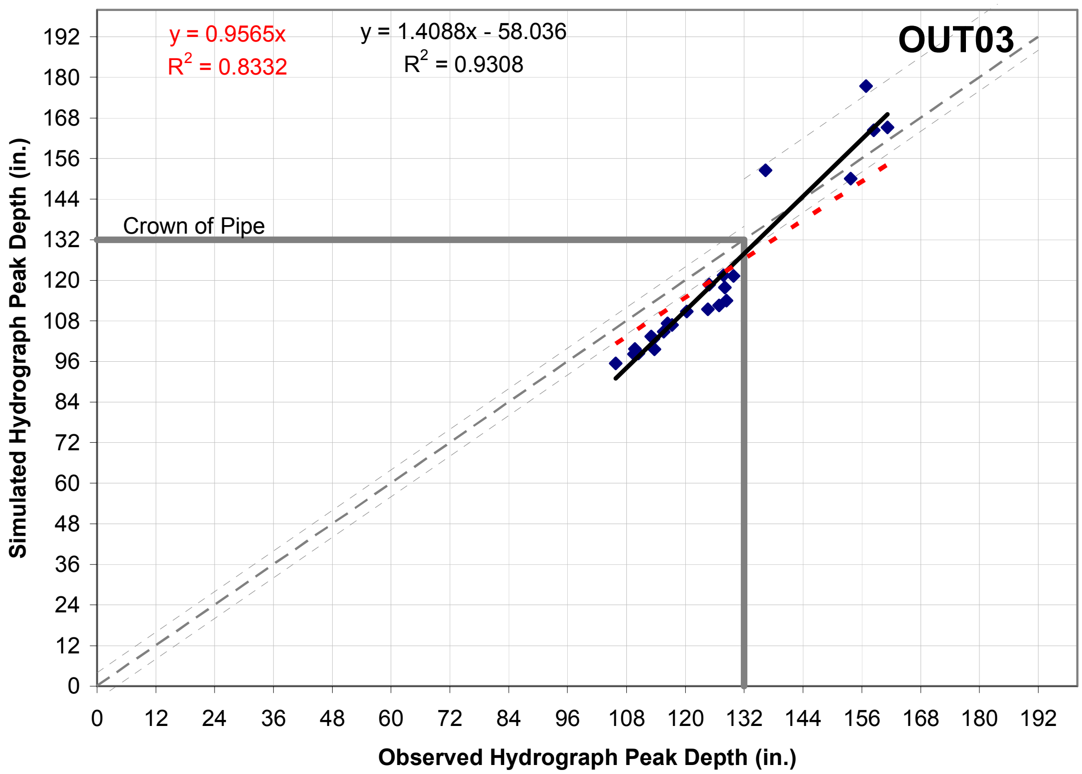
Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 10 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

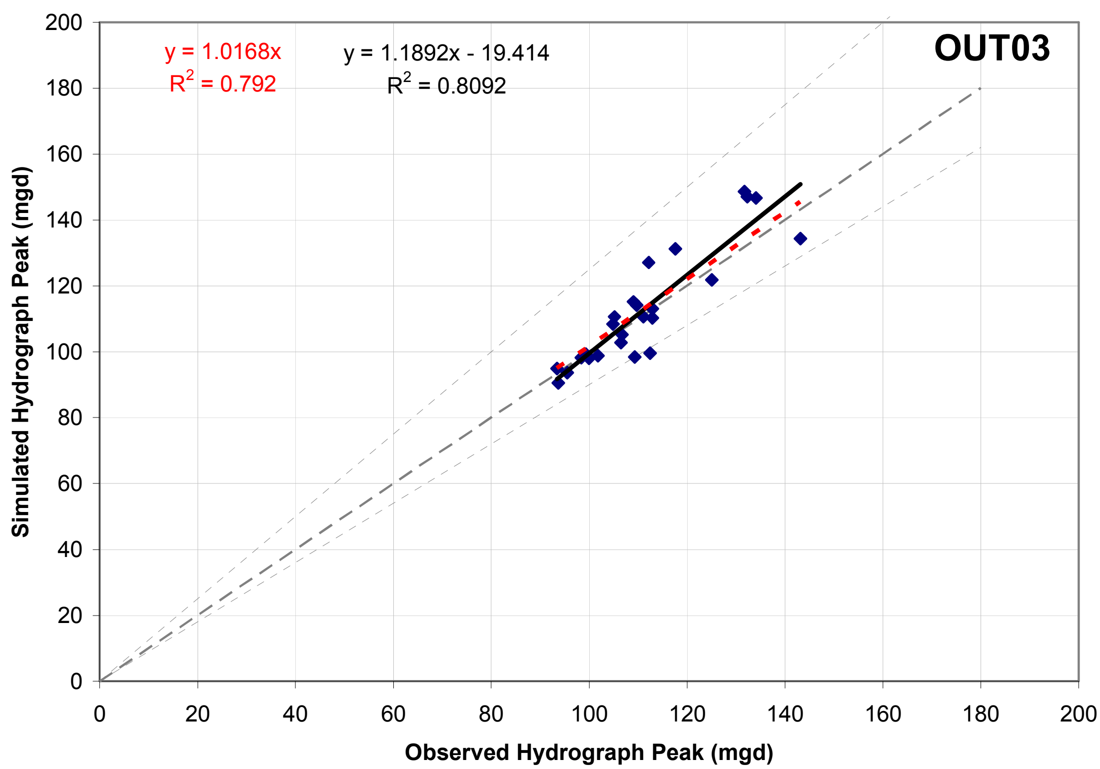
Flow Survey Location (Obs.) OUT03, Model Location (Pred.) D/S S55AA_001MH.1, Rainfall Profile: 13

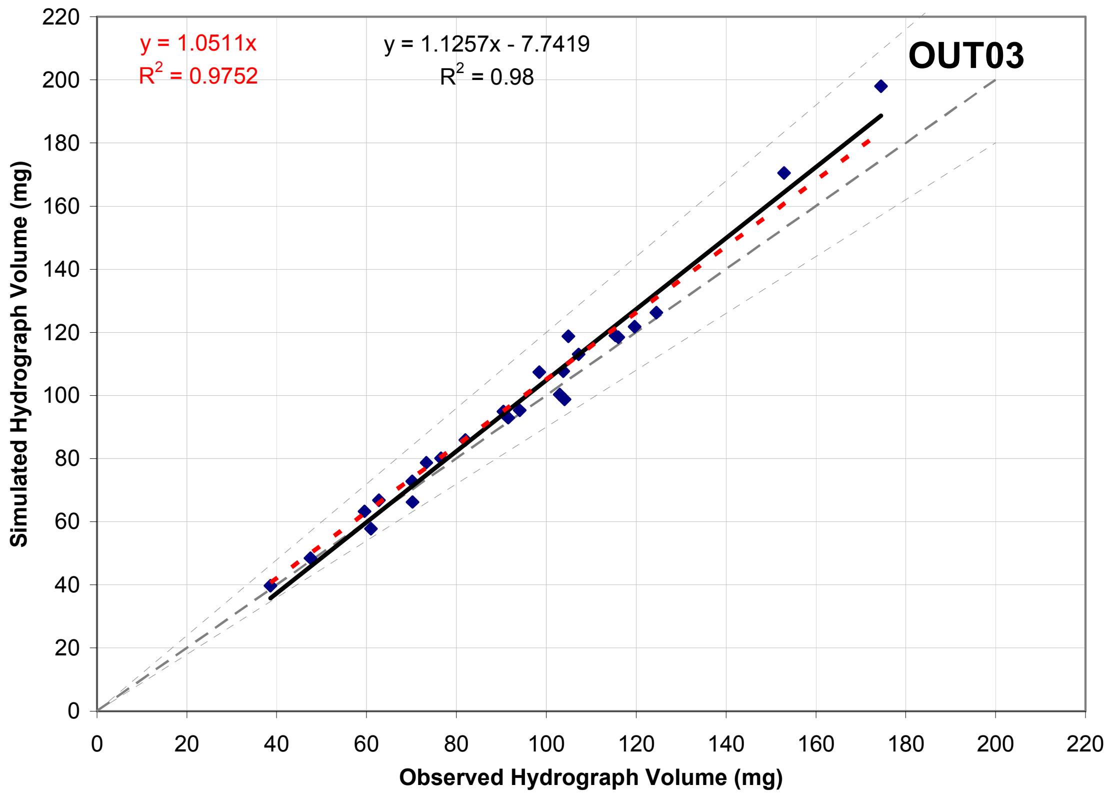


	Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
	Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain	34.789	1.292	0.004							
Obs.				0.000	15.199	0.000	161.604	27699.698	0.000	2.677
...>ModelSim>A18>GaugeRain				4.931	15.147	-26.547	147.765	28569.857	-0.603	2.519
...>ModelSim>A18>RadarRain				4.928	15.123	-26.547	148.730	28535.575	-0.603	2.519

OUT03

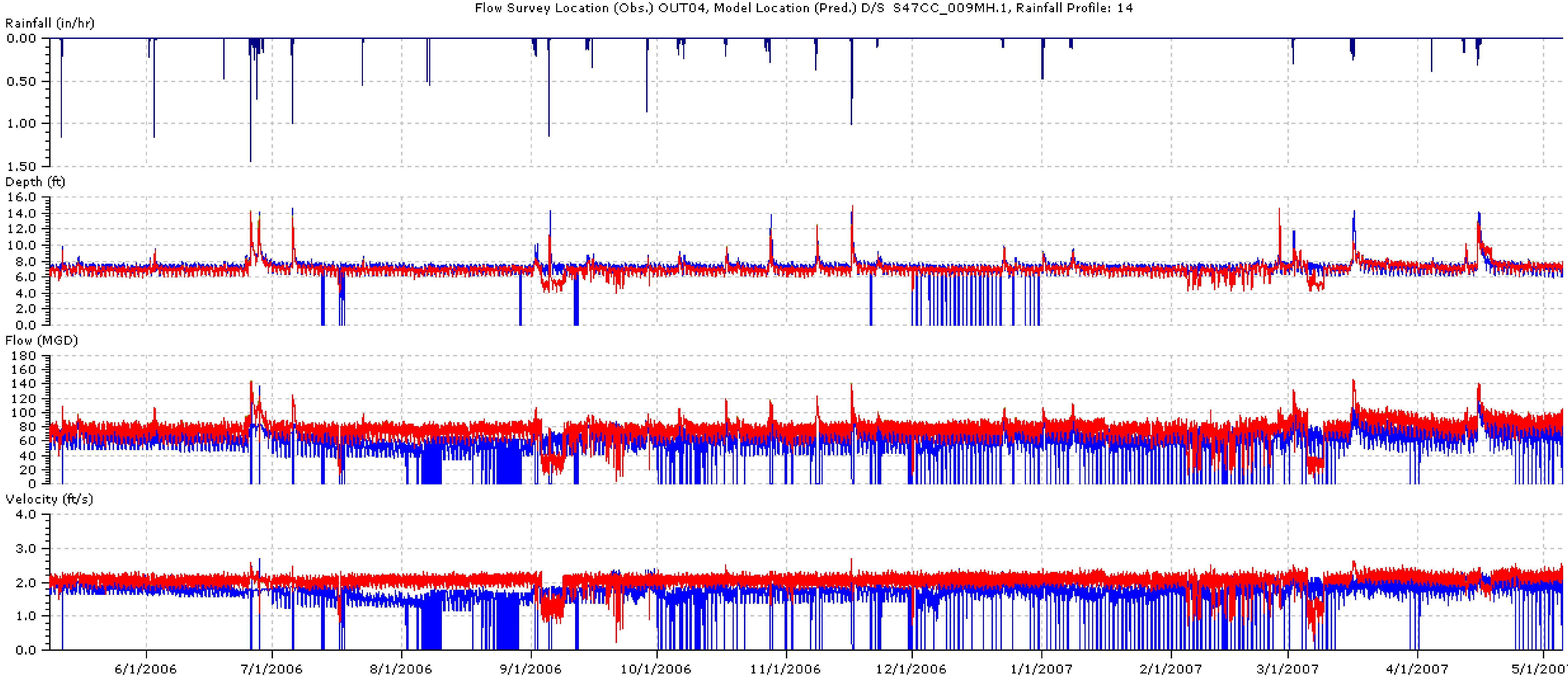

y = 0.9565x
R2 = 0.8332
y = 1.4088x - 58.036
R2 = 0.9308
OUT03
Crown of Pipe
Simulated Hydrograph Peak Depth (in.)
Observed Hydrograph Peak Depth (in.)
0
12
24
36
48
60
72
84
96
108
120
132
144
156
168
180
192


y = 1.0168x
R2 = 0.792
y = 1.1892x - 19.414
R2 = 0.8092
OUT03
Simulated Hydrograph Peak (mgd)
Observed Hydrograph Peak (mgd)
0
20
40
60
80
100
120
140
160
180
200


y = 1.0511x
R^2 = 0.9752
y = 1.1257x - 7.7419
R^2 = 0.98
OUT03
Simulated Hydrograph Volume (mg)
Observed Hydrograph Volume (mg)
0
20
40
60
80
100
120
140
160
180
200
220

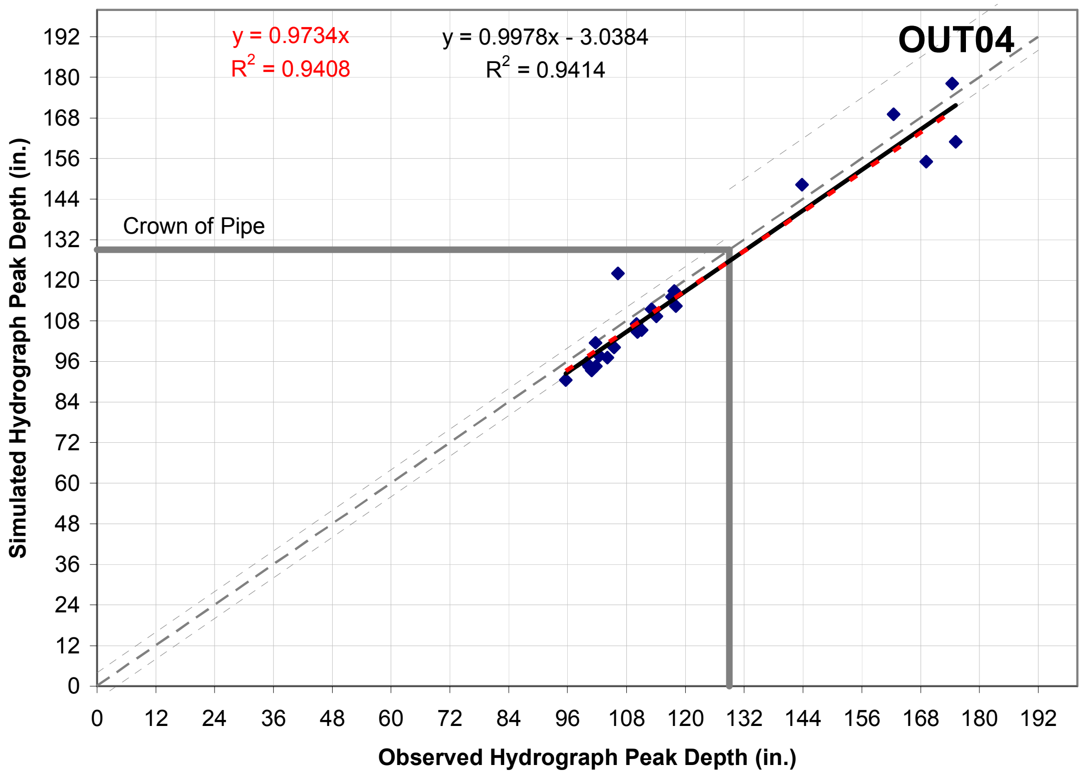
Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 11 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

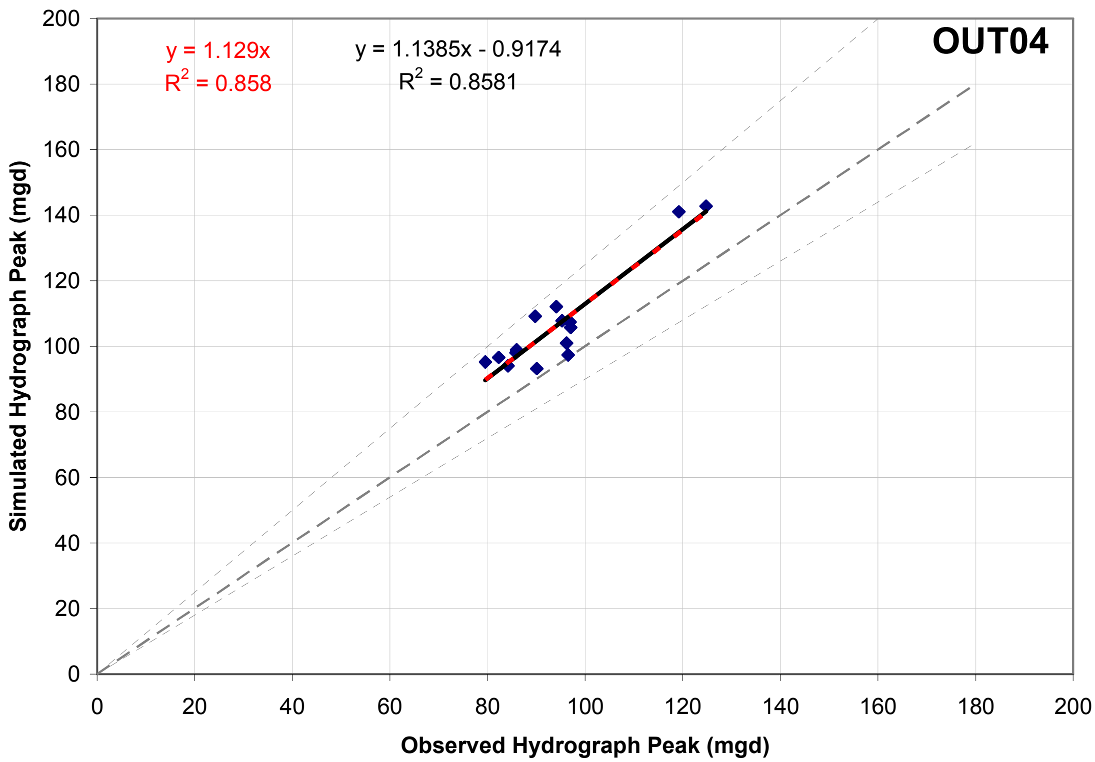
Flow Survey Location (Obs.) OUT04, Model Location (Pred.) D/S S47CC_009MH.1, Rainfall Profile: 14

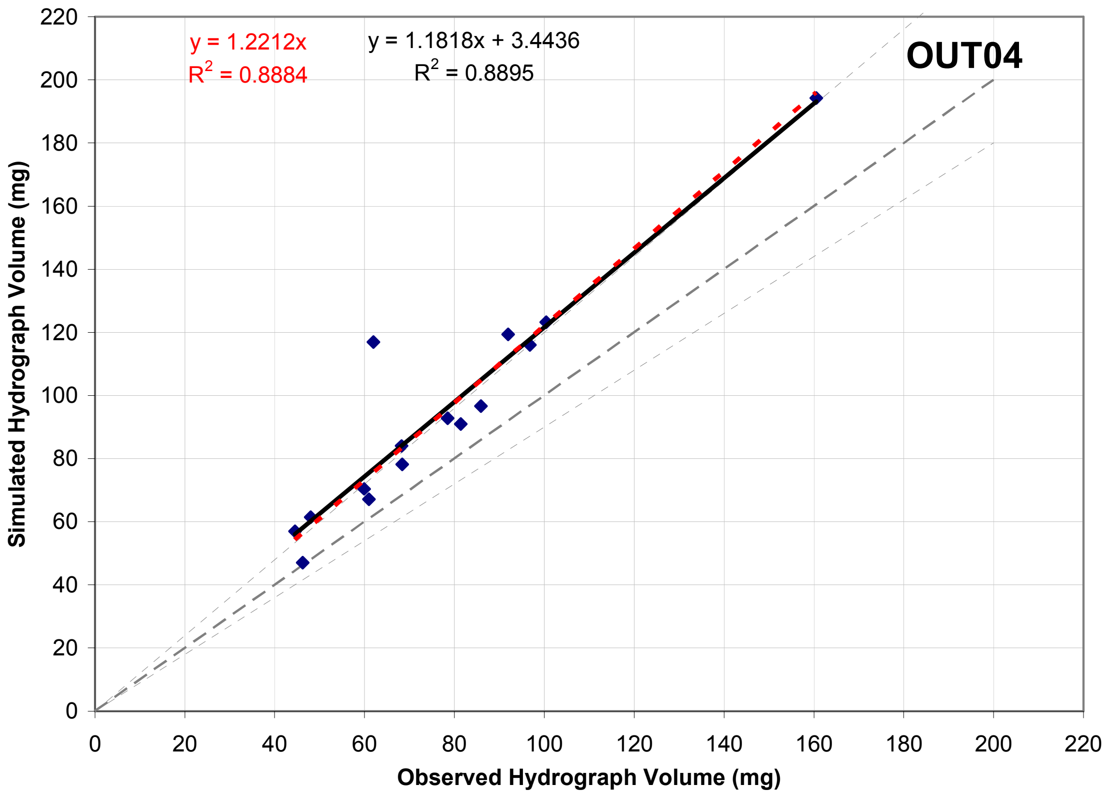


	Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
	Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain	34.755	1.434	0.004							
Obs.				0.000	14.600	0.000	137.600	21358.567	0.000	2.700
...>ModelSim>A18>GaugeRain				3.885	14.918	3.080	145.298	27905.704	0.227	2.698
...>ModelSim>A18>RadarRain				3.885	14.816	3.079	145.936	27887.322	0.227	2.701

OUT04


y = 0.9734x
R^2 = 0.9408
y = 0.9978x - 3.0384
R^2 = 0.9414
OUT04
Crown of Pipe
Simulated Hydrograph Peak Depth (in.)
Observed Hydrograph Peak Depth (in.)
0
12
24
36
48
60
72
84
96
108
120
132
144
156
168
180
192


y = 1.129x
R^2 = 0.858
y = 1.1385x - 0.9174
R^2 = 0.8581
OUT04
Simulated Hydrograph Peak (mgd)
Observed Hydrograph Peak (mgd)
0
20
40
60
80
100
120
140
160
180
200



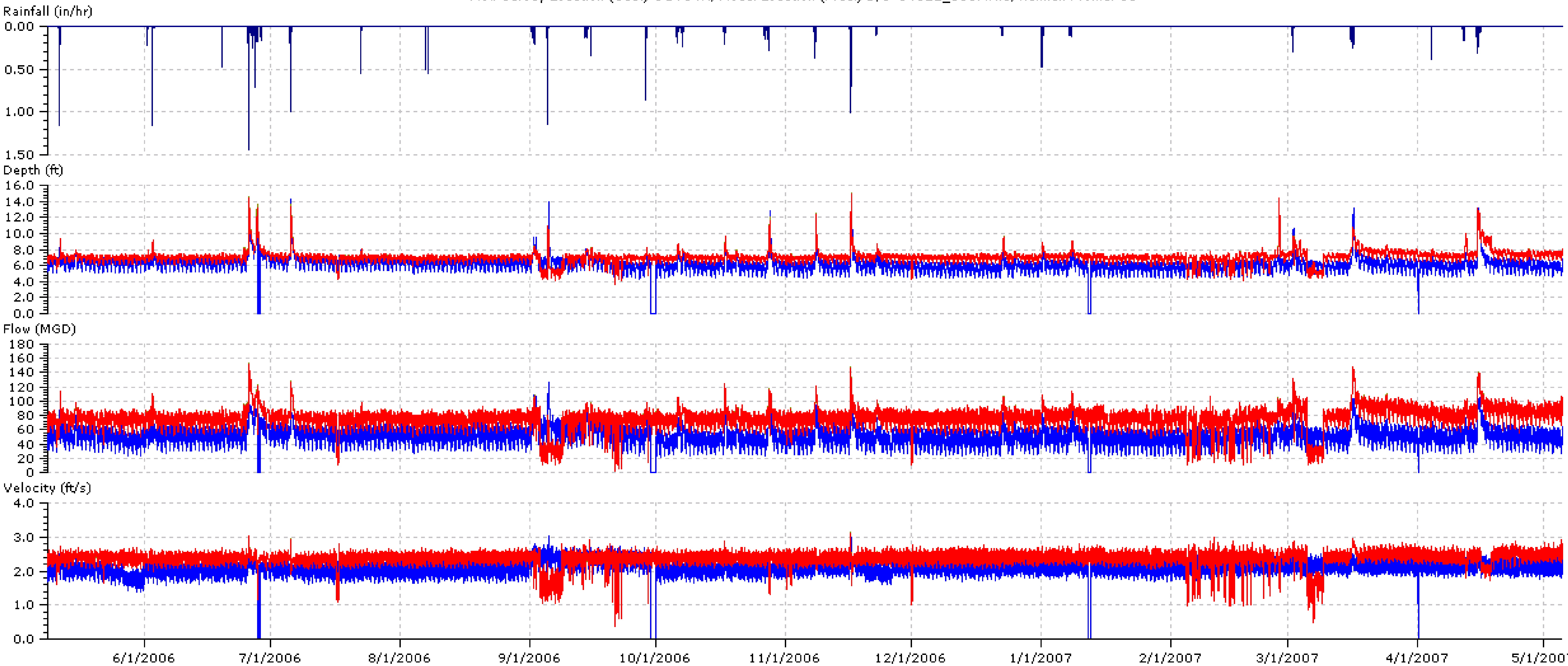
Notes:

An Isco meter was used to monitor flow at OUT04. Measured velocity and flow rate values at OUT04 are low compared to neighboring meters at TSHL01 and OUT02 that have FlowShark meters. Based on the conservation of mass, it is recognized that the measured flow values at OUT04 have a low bias of approximately 22%.

Measured depth values at OUT04 are within calibration tolerance but are typically 3% high.

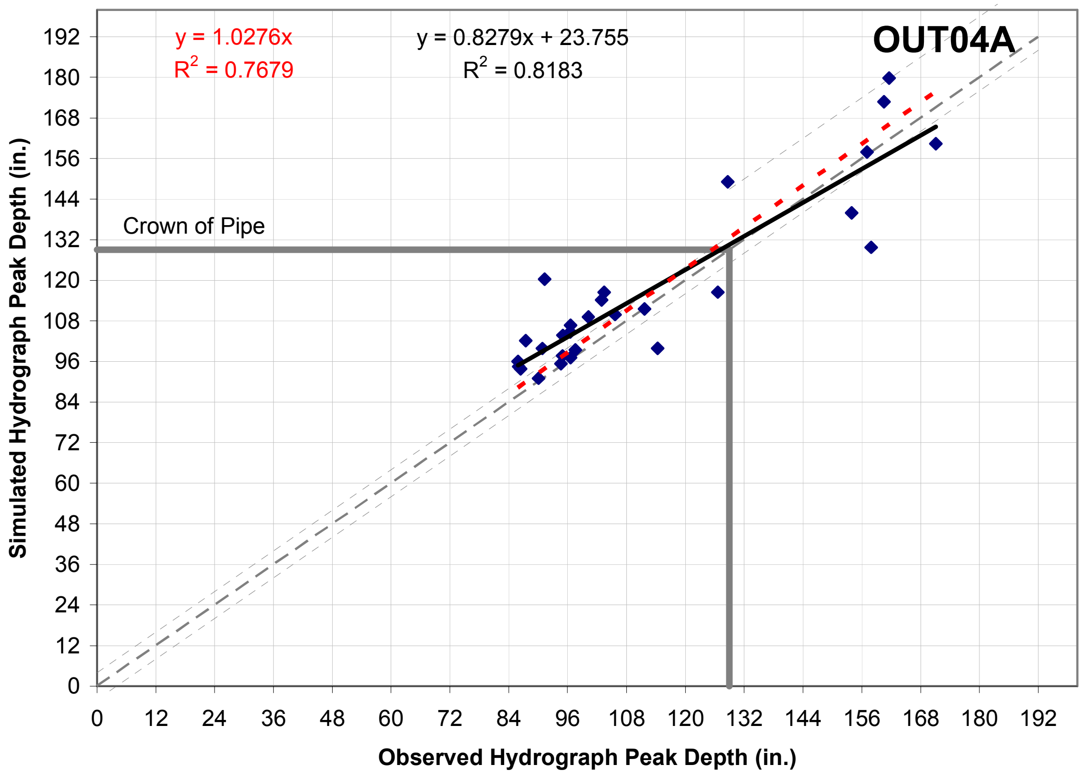
Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 12 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

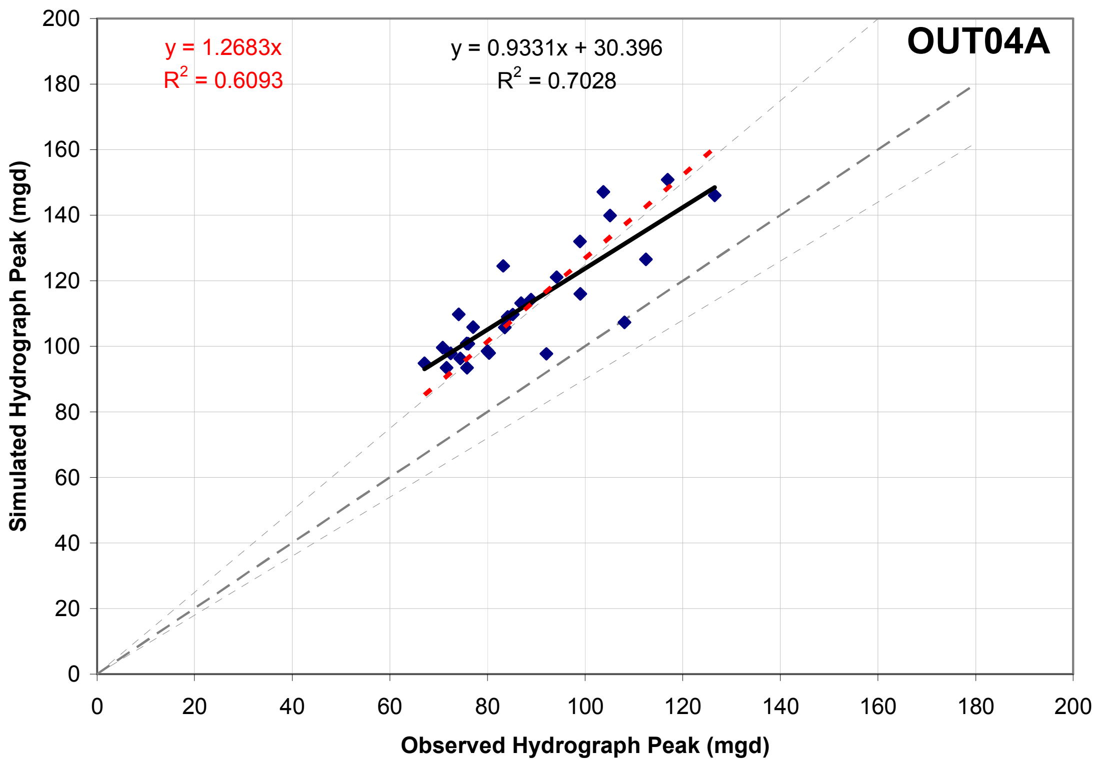
Flow Survey Location (Obs.) OUT04A, Model Location (Pred.) D/S S45EE_016MH.1, Rainfall Profile: 15

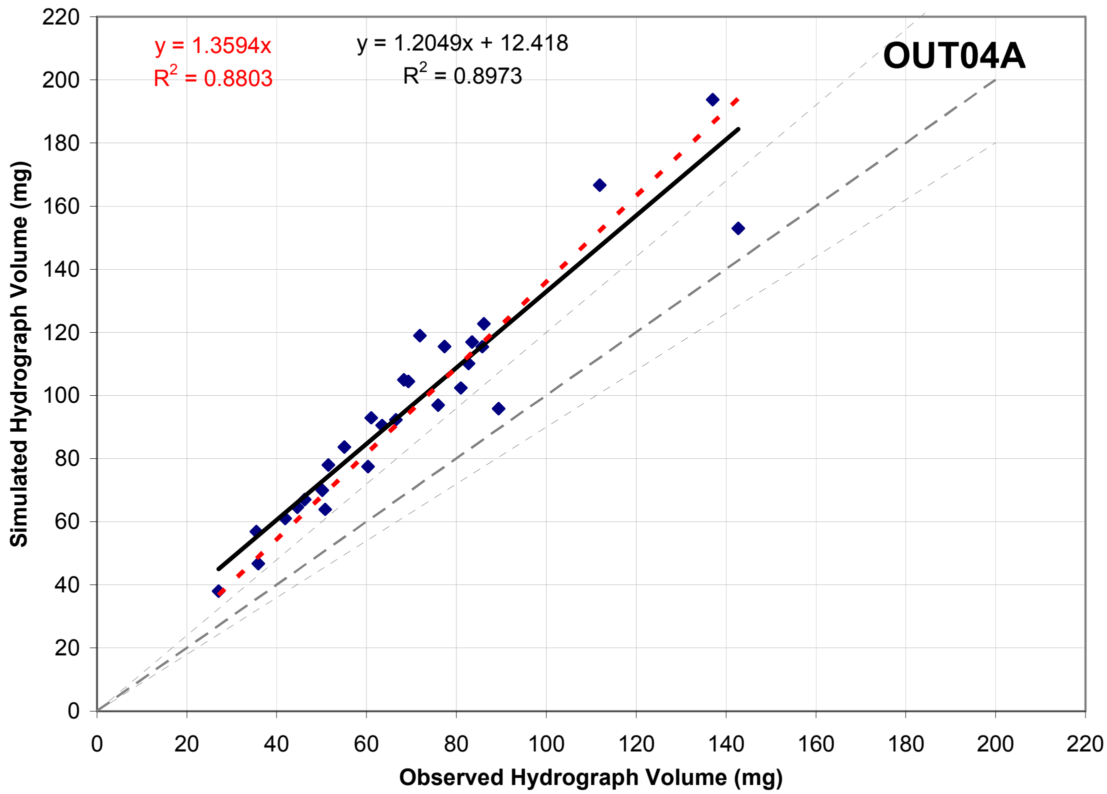


	Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
	Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain	34.755	1.434	0.004							
Obs.				0.000	14.259	0.000	127.333	18683.713	0.000	3.017
...>ModelSim>A18>GaugeRain				3.615	15.057	2.108	153.420	27792.330	0.370	3.135
...>ModelSim>A18>RadarRain				3.615	14.949	2.107	150.704	27773.659	0.370	3.121

OUT04A


y = 1.0276x
R^2 = 0.7679
y = 0.8279x + 23.755
R^2 = 0.8183
OUT04A
Crown of Pipe
Simulated Hydrograph Peak Depth (in.)
Observed Hydrograph Peak Depth (in.)
0
12
24
36
48
60
72
84
96
108
120
132
144
156
168
180
192


y = 1.2683x
R^2 = 0.6093
y = 0.9331x + 30.396
R^2 = 0.7028
OUT04A
Simulated Hydrograph Peak (mgd)
Observed Hydrograph Peak (mgd)
0
20
40
60
80
100
120
140
160
180
200



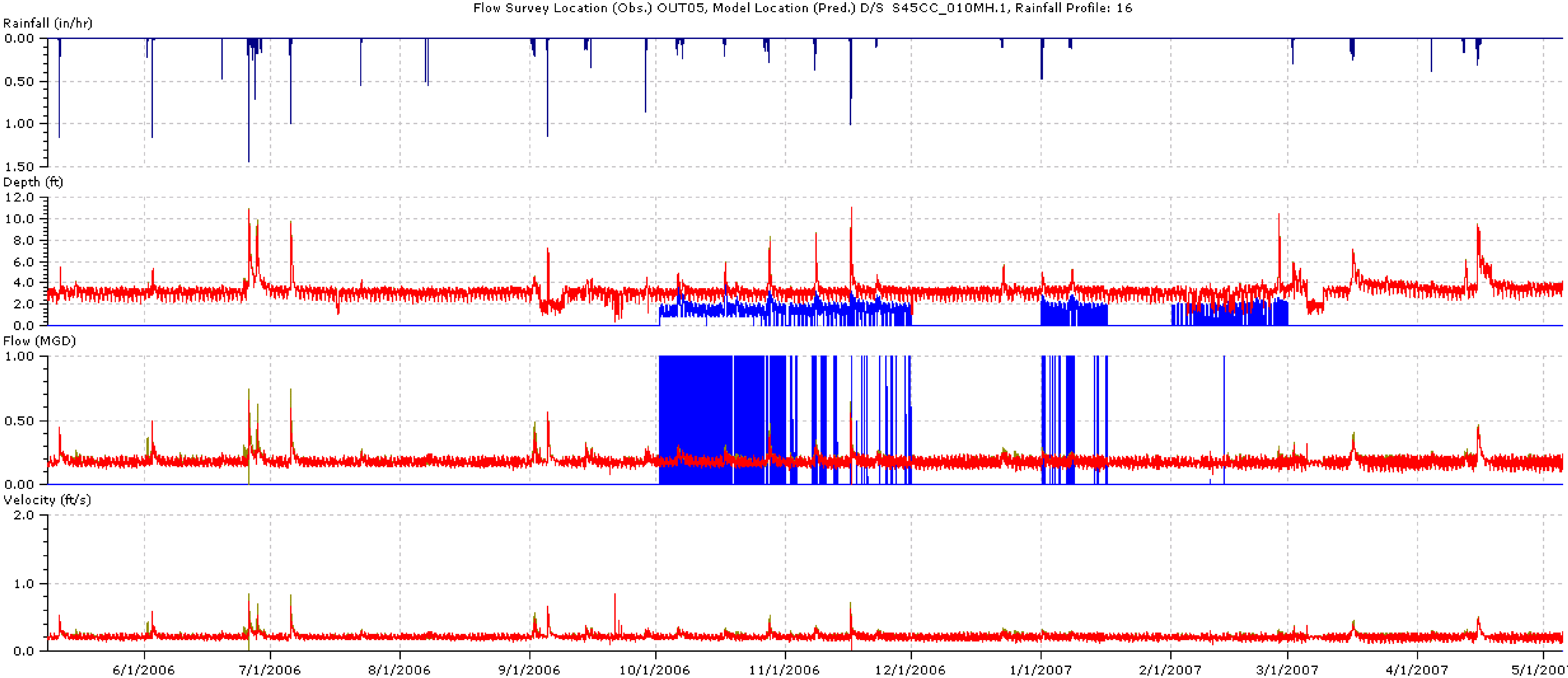
Notes:

An Isco meter was used to monitor flow at OUT04A. Measured velocity and flow rate values at OUT04A are low compared to neighboring meters at TSHL01 and OUT02 that have FlowShark meters. Based on the conservation of mass, it is recognized that the measured flow values at OUT04A have a low bias of approximately 35%.

Measured depth values at OUT04A have more variability than at neighboring meters; this may indicate local flow disturbances in the vicinity of the meter.

Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 13 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

Flow Survey Location (Obs.) OUT05, Model Location (Pred.) D/S S45CC_010MH.1, Rainfall Profile: 16

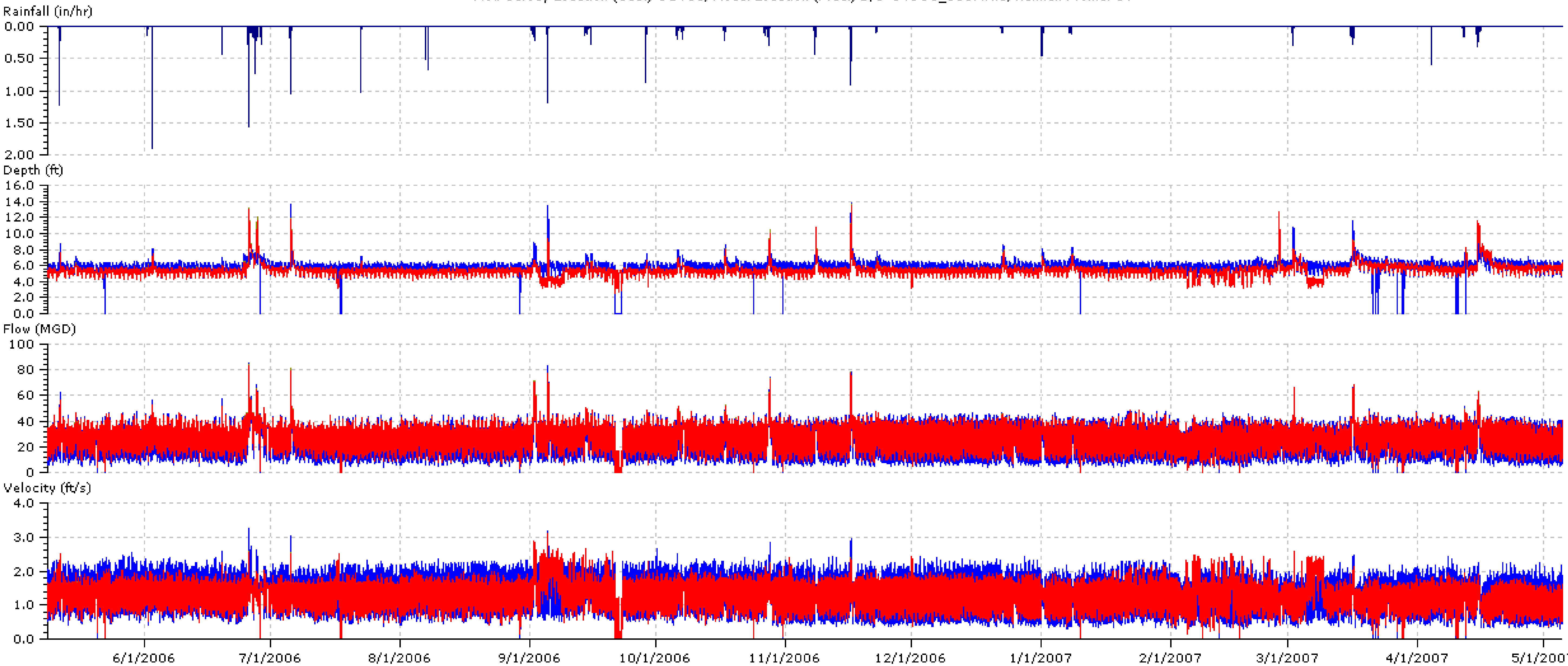


		Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
		Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain		34.755	1.434	0.004							
Obs.					0.000	4.143	0.000	12.150	90.342	0.000	0.000
...>ModelSim>A18>GaugeRain					0.402	11.100	-1.689	0.747	65.453	-1.723	0.837
...>ModelSim>A18>RadarRain					0.402	11.072	-1.520	0.658	63.952	-1.552	0.836

OUT05

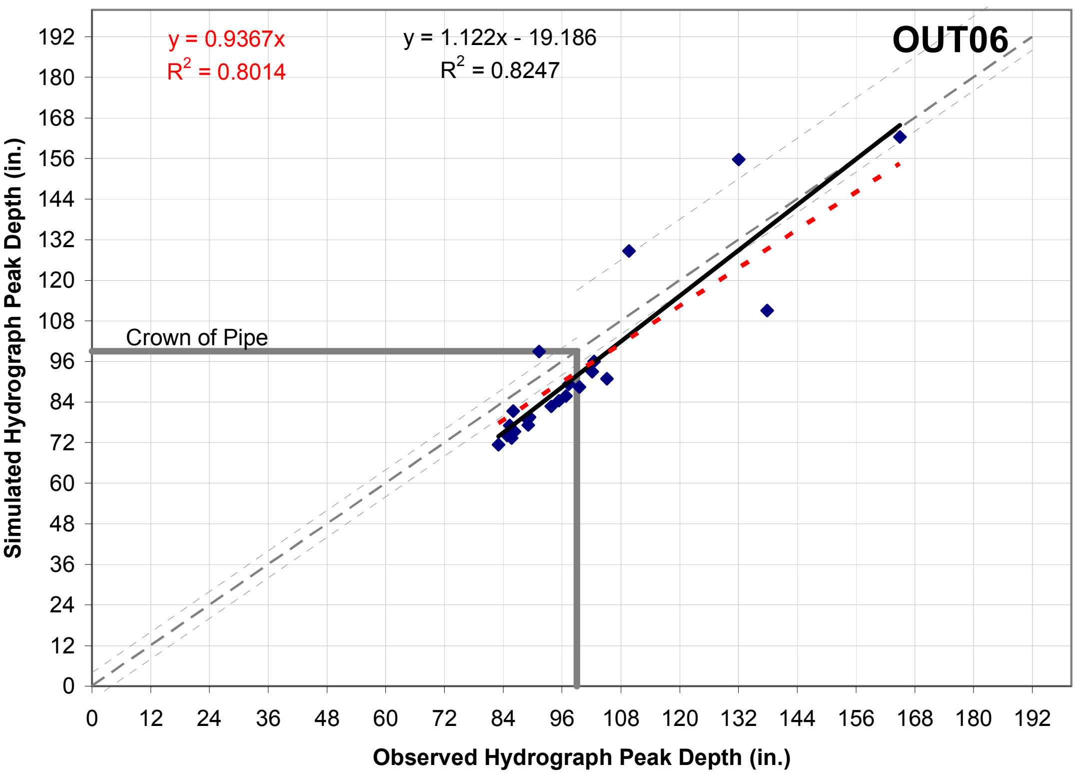
Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 14 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

Flow Survey Location (Obs.) OUT06, Model Location (Pred.) D/S S45CC_006MH.1, Rainfall Profile: 17

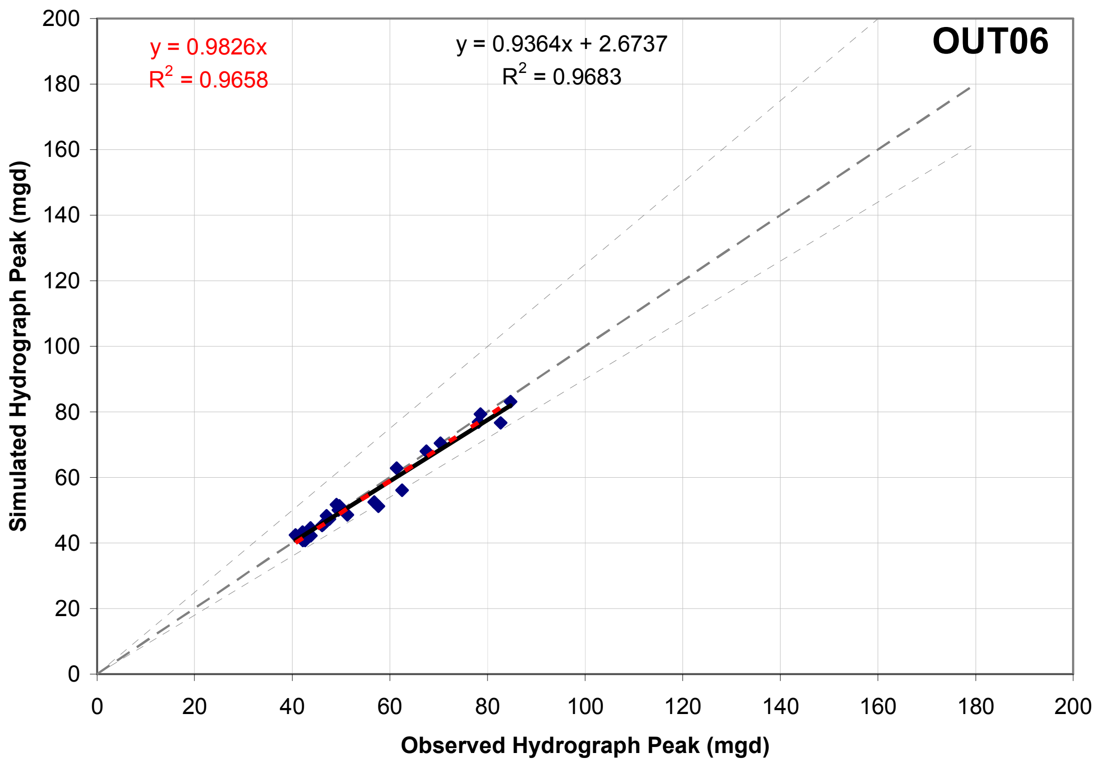


		Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
		Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain		36.161	1.894	0.004							
Obs.					0.000	13.746	0.000	84.721	9764.105	0.000	3.257
...>ModelSim>A18>GaugeRain					2.510	13.610	-15.948	84.511	10059.549	-1.341	3.101
...>ModelSim>A18>RadarRain					2.510	13.500	-15.948	83.033	10050.566	-1.341	3.089

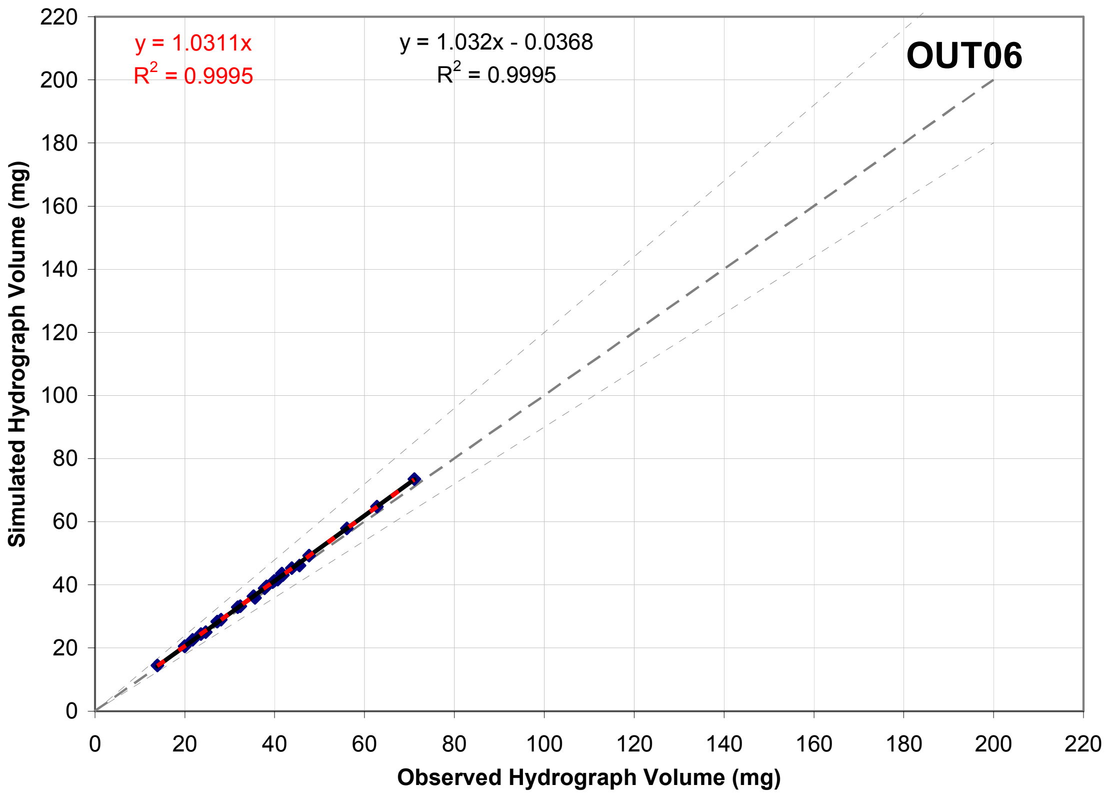
OUT06



y = 0.9367x
R^2 = 0.8014
y = 1.122x - 19.186
R^2 = 0.8247
OUT06
Crown of Pipe
Simulated Hydrograph Peak Depth (in.)
Observed Hydrograph Peak Depth (in.)
0
12
24
36
48
60
72
84
96
108
120
132
144
156
168
180
192



y = 0.9826x
R^2 = 0.9658
y = 0.9364x + 2.6737
R^2 = 0.9683
OUT06
Simulated Hydrograph Peak (mgd)
Observed Hydrograph Peak (mgd)
0
20
40
60
80
100
120
140
160
180
200



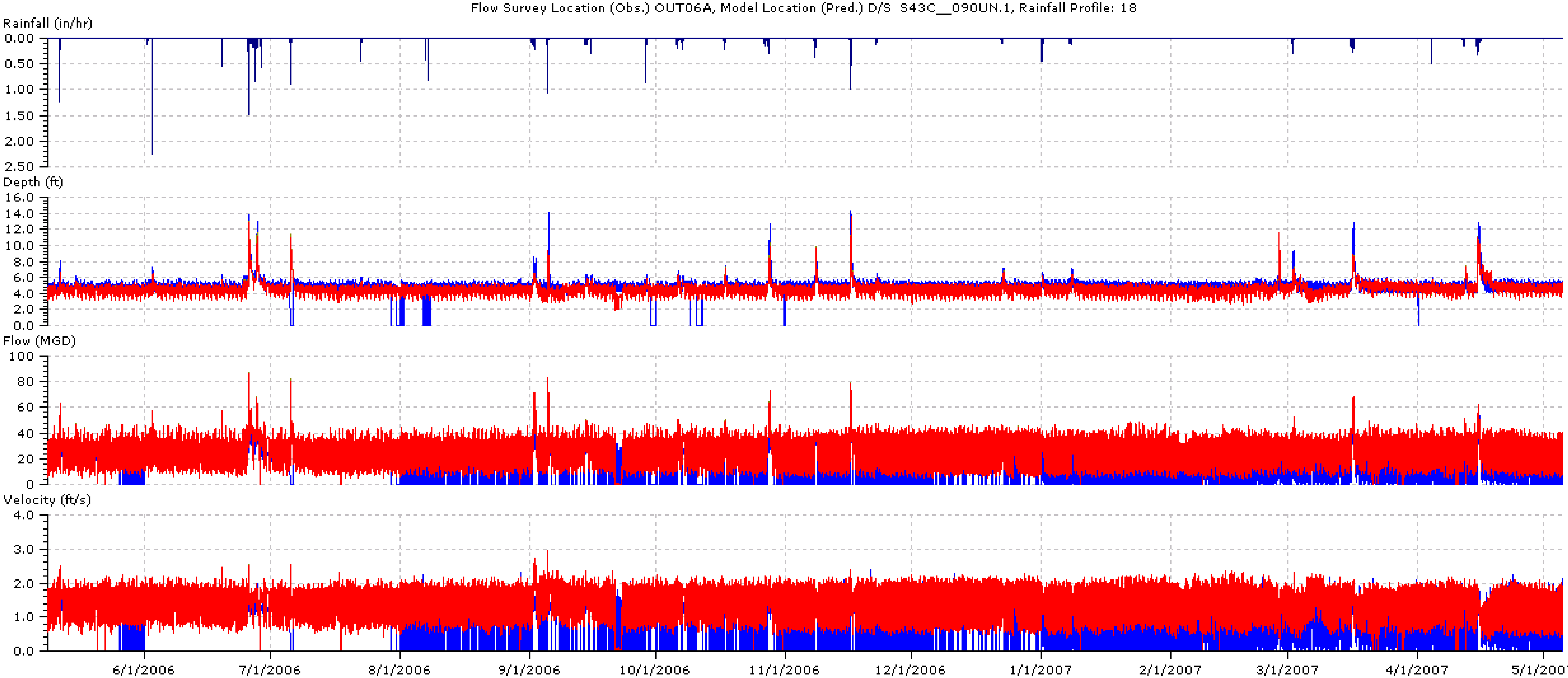
Notes:

Meter site OUT06 is located near the downstream end of the 99-inch sewer that conveys flow from the Eastern Avenue Pump Station force main. The flow at OUT06 is strongly influenced by the operations of the pump station; therefore, the measured values have a high degree of variability.

A FlowShark meter was used to monitor flow at OUT06.

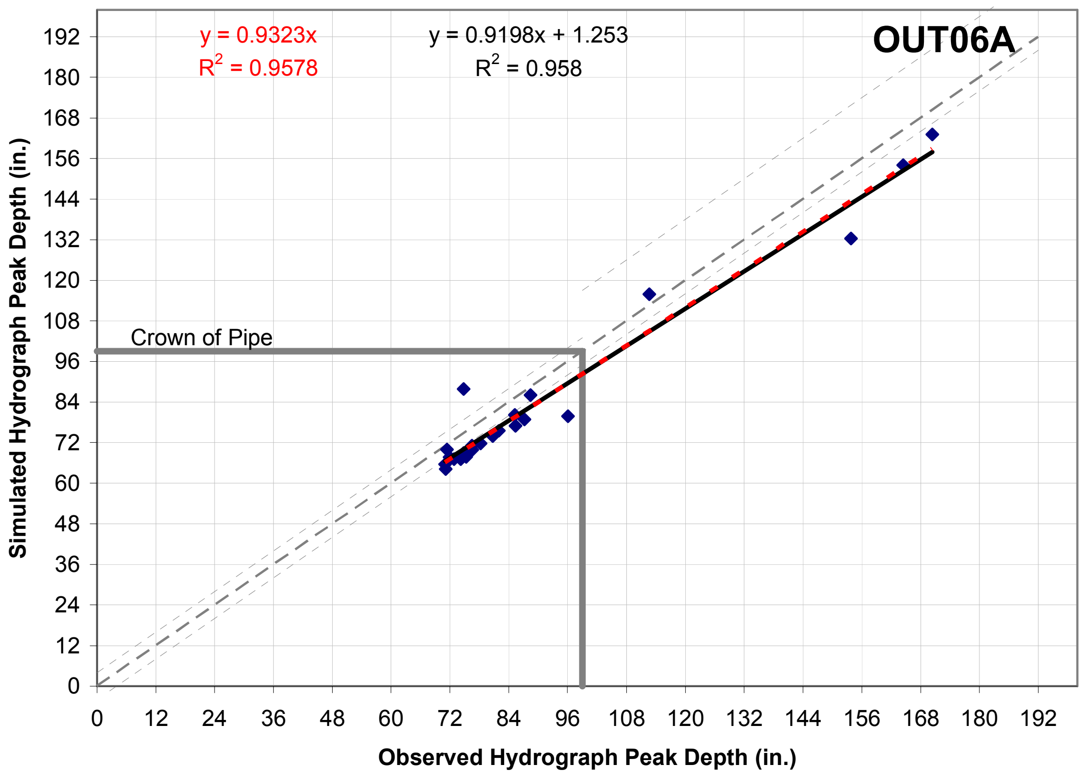
Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 15 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

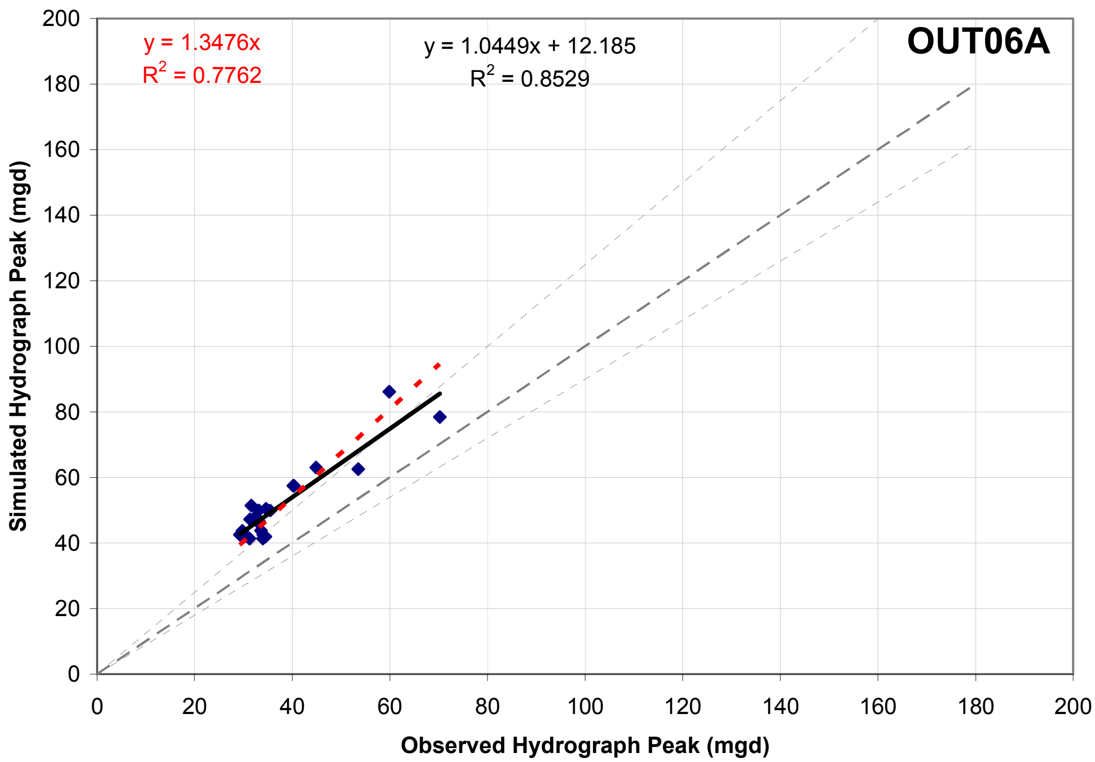
Flow Survey Location (Obs.) OUT06A, Model Location (Pred.) D/S S43C__090UN.1, Rainfall Profile: 18

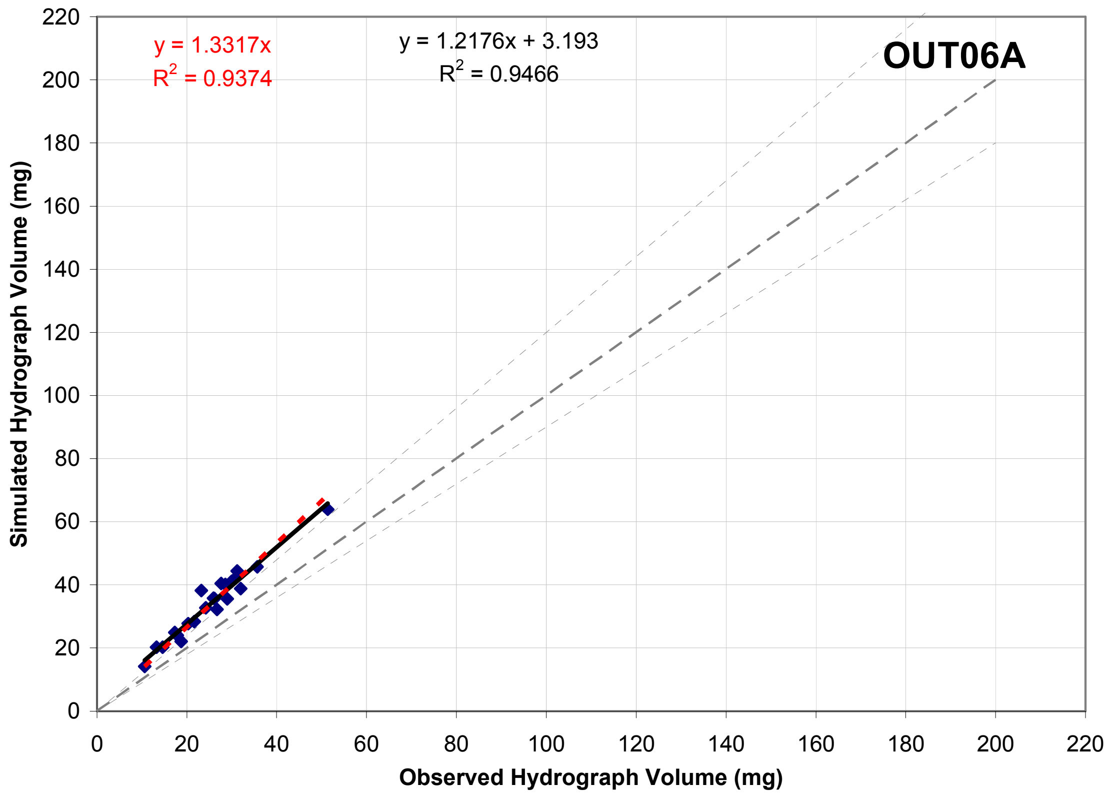


		Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
		Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain		35.945	2.248	0.004							
Obs.					0.000	14.198	0.000	70.220	7402.744	0.000	2.380
...>ModelSim>A18>GaugeRain					1.972	13.670	-0.106	86.717	9864.800	-0.021	2.938
...>ModelSim>A18>RadarRain					1.972	13.558	-0.106	86.037	9859.908	-0.021	2.939

OUT06A


y = 0.9323x
R2 = 0.9578
y = 0.9198x + 1.253
R2 = 0.958
OUT06A
Crown of Pipe
Simulated Hydrograph Peak Depth (in.)
Observed Hydrograph Peak Depth (in.)


y = 1.3476x
R2 = 0.7762
y = 1.0449x + 12.185
R2 = 0.8529
OUT06A
Simulated Hydrograph Peak (mgd)
Observed Hydrograph Peak (mgd)



Notes:

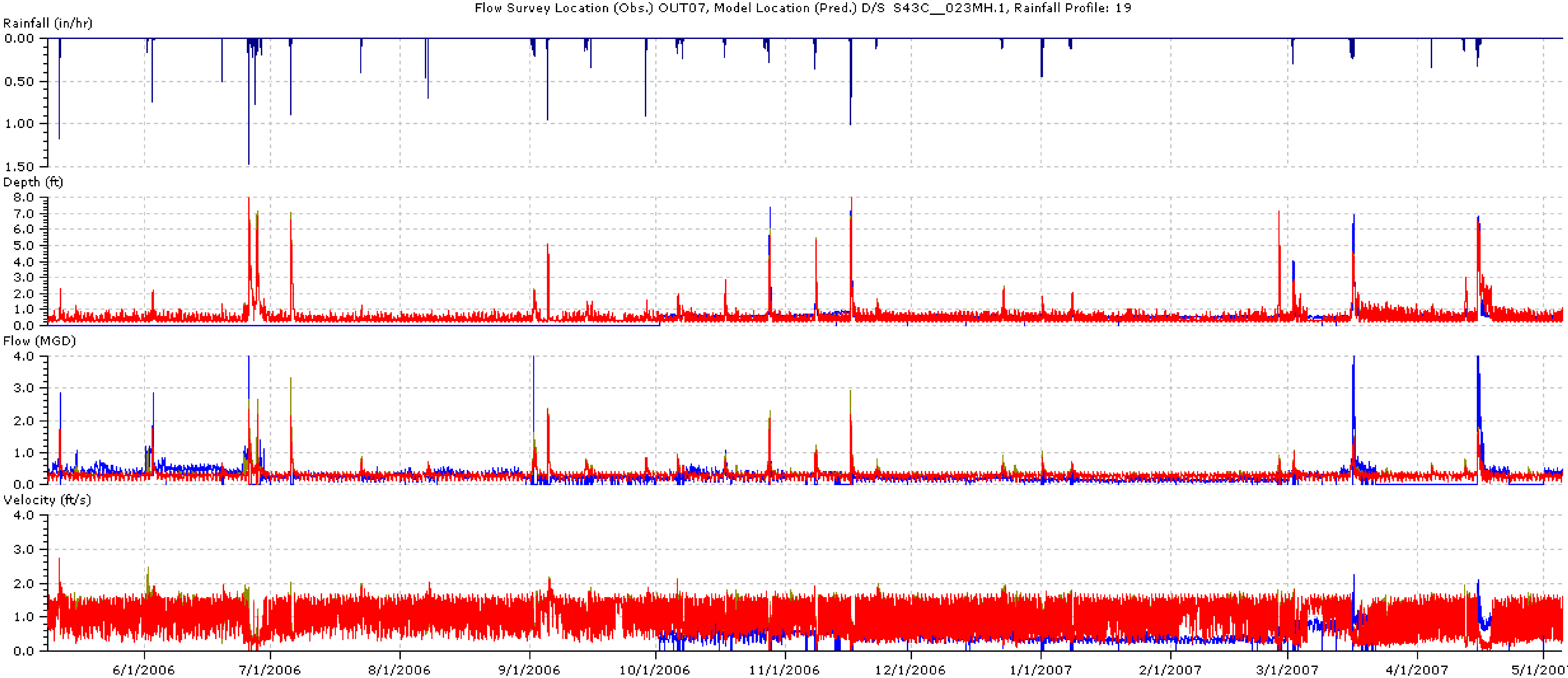
Meter site OUT06A is located at the upstream end of the 99-inch sewer that conveys flow from the Eastern Avenue Pump Station force main. The flow at OUT06A is strongly influenced by the operations of the pump station; therefore, the measured values have a high degree of variability.

An Isco meter was used to monitor flow at OUT06A. Measured velocity and flow rate values at OUT06A are low compared to the neighboring downstream meter at OUT06 that has a FlowShark meter. Based on the conservation of mass, the measured flow values at OUT06A may have a low bias of approximately 33%.

During times of low flow, the recorded velocity values are frequently equal to zero.

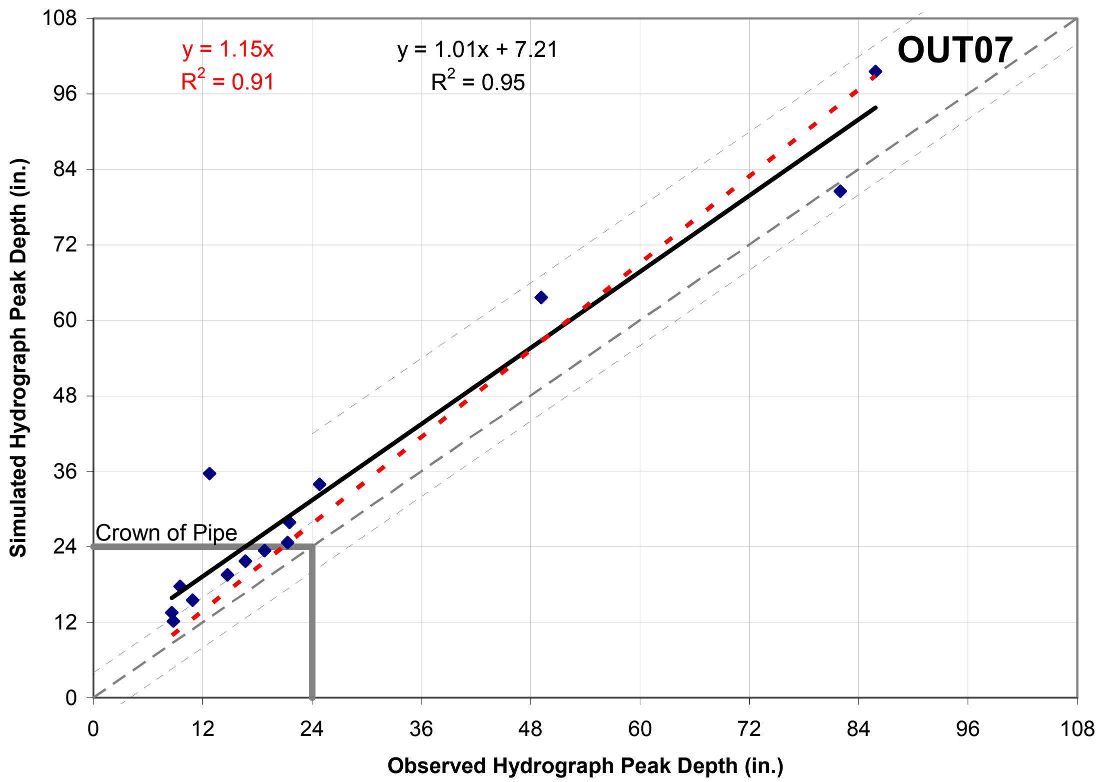
Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 16 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

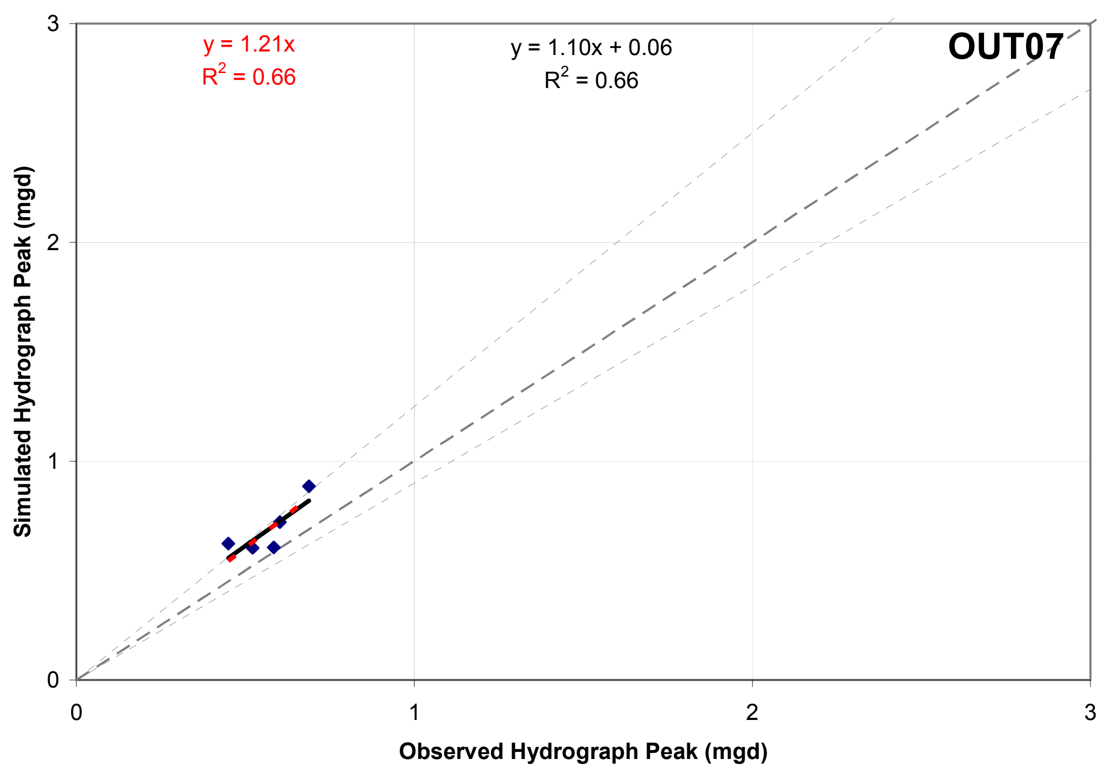
Flow Survey Location (Obs.) OUT07, Model Location (Pred.) D/S S43C__023MH.1, Rainfall Profile: 19

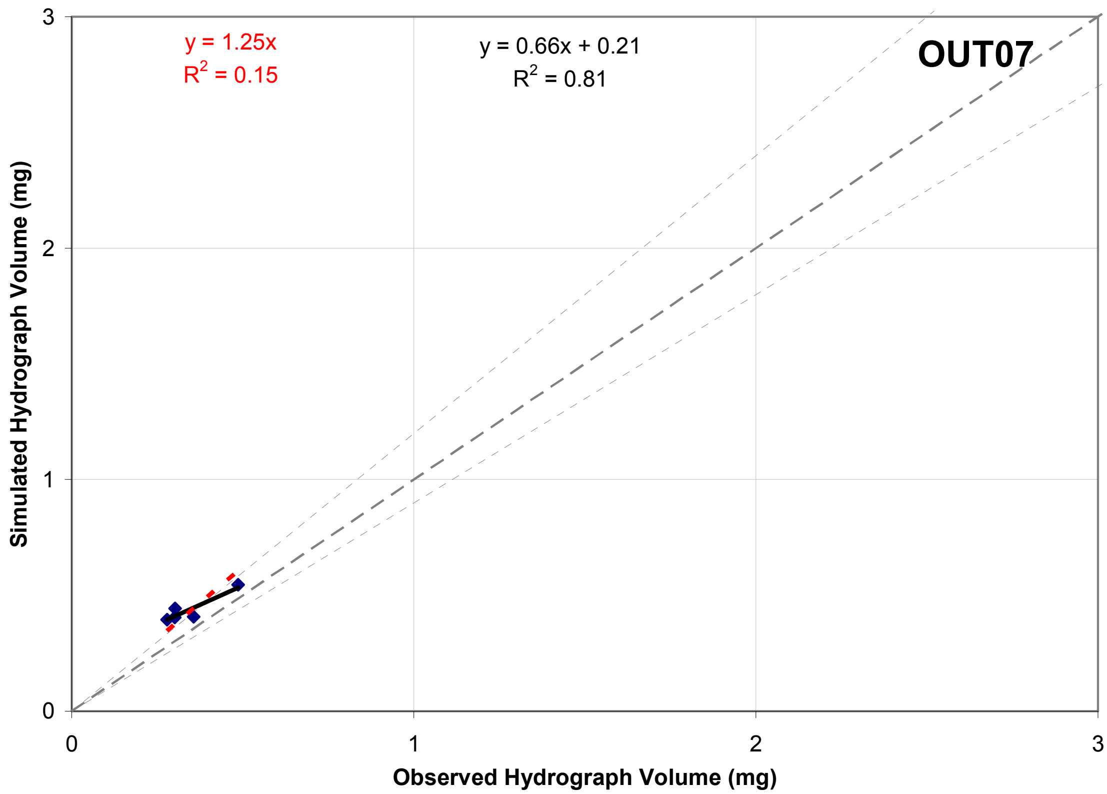


	Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
	Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain	34.415	1.474	0.004							
Obs.				0.000	7.347	0.000	11.142	87.591	0.000	2.225
...>ModelSim>A18>GaugeRain				0.212	8.362	-7.174	3.323	109.148	-3.166	2.533
...>ModelSim>A18>RadarRain				0.212	8.299	-6.990	2.353	104.040	-3.087	2.720

OUT07


y = 1.15x
R2 = 0.91
y = 1.01x + 7.21
R2 = 0.95
OUT07
Crown of Pipe
Simulated Hydrograph Peak Depth (in.)
Observed Hydrograph Peak Depth (in.)
0
12
24
36
48
60
72
84
96
108


y = 1.21x
R2 = 0.66
y = 1.10x + 0.06
R2 = 0.66
OUT07
Simulated Hydrograph Peak (mgd)
Observed Hydrograph Peak (mgd)
0
1
2
3



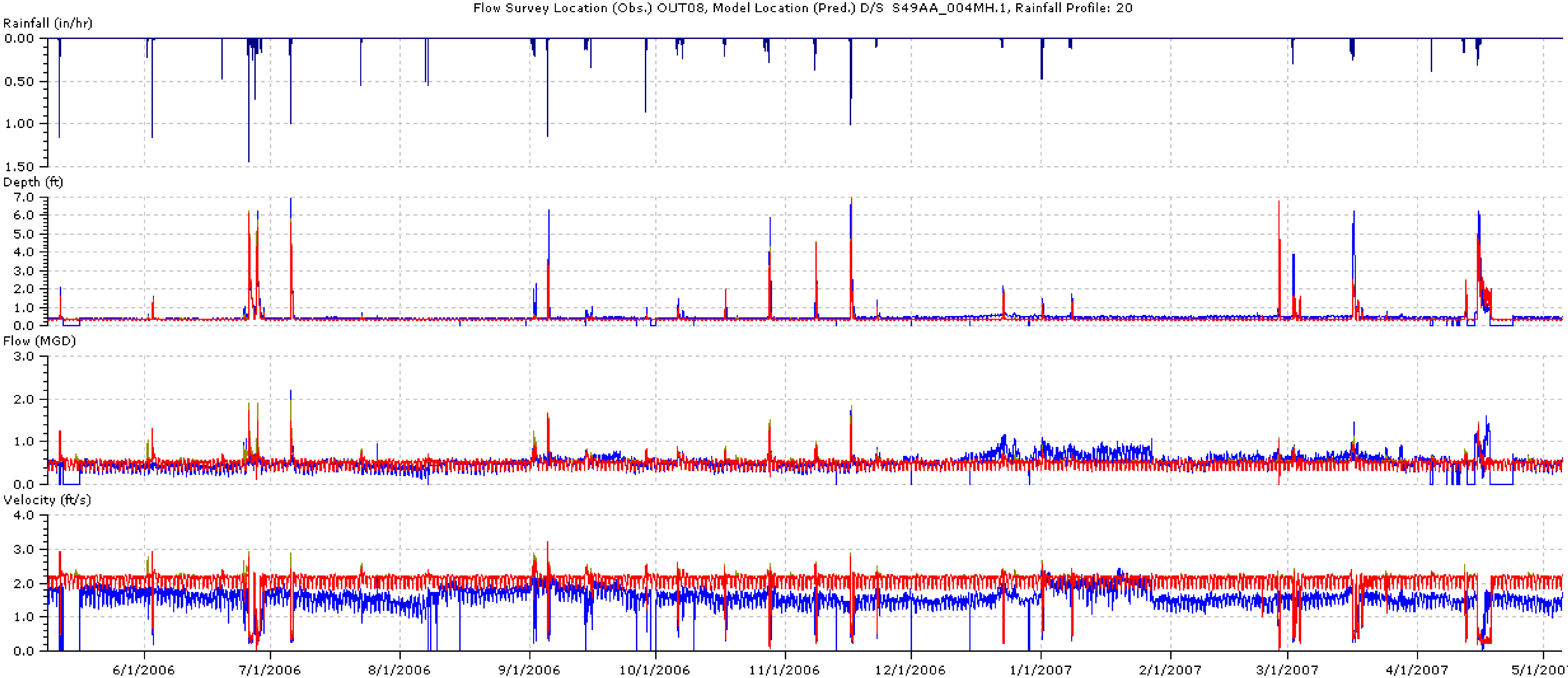
Notes:

Meter OUT07 is an Isco meter mounted in the branch sewer that connects to the upstream end of the 99-inch sewer. Meter OUT09 is a FlowShark meter on the same sewer, approximately five hundred linear feet downstream. Both OUT07 and OUT09 experience surcharging due to high water levels in the 99-inch sewer. The surcharging may be associated with episodes of reverse flow in the sewer. Peak measured flows may be associated with flow reversals and may not be an indication of peak flow generated in the meter basin area.

Measured velocities are very low (less than 1 ft/s), which is a cause for greater uncertainty in the measured flow values.

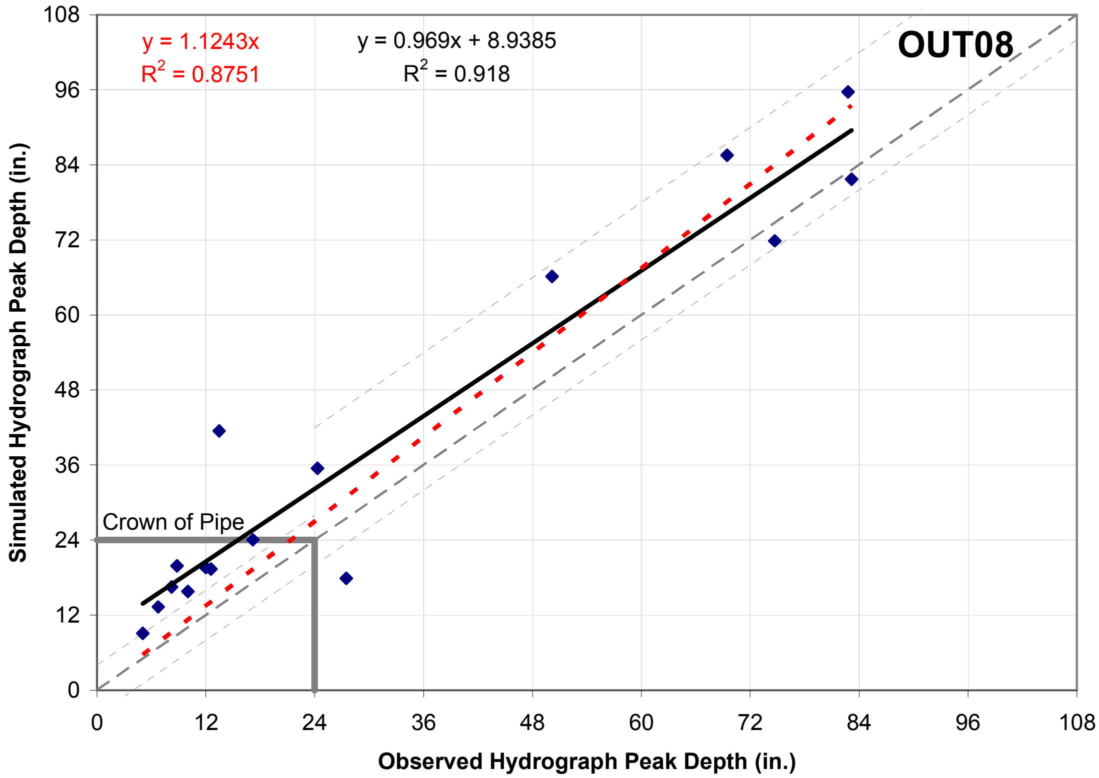
Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 17 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

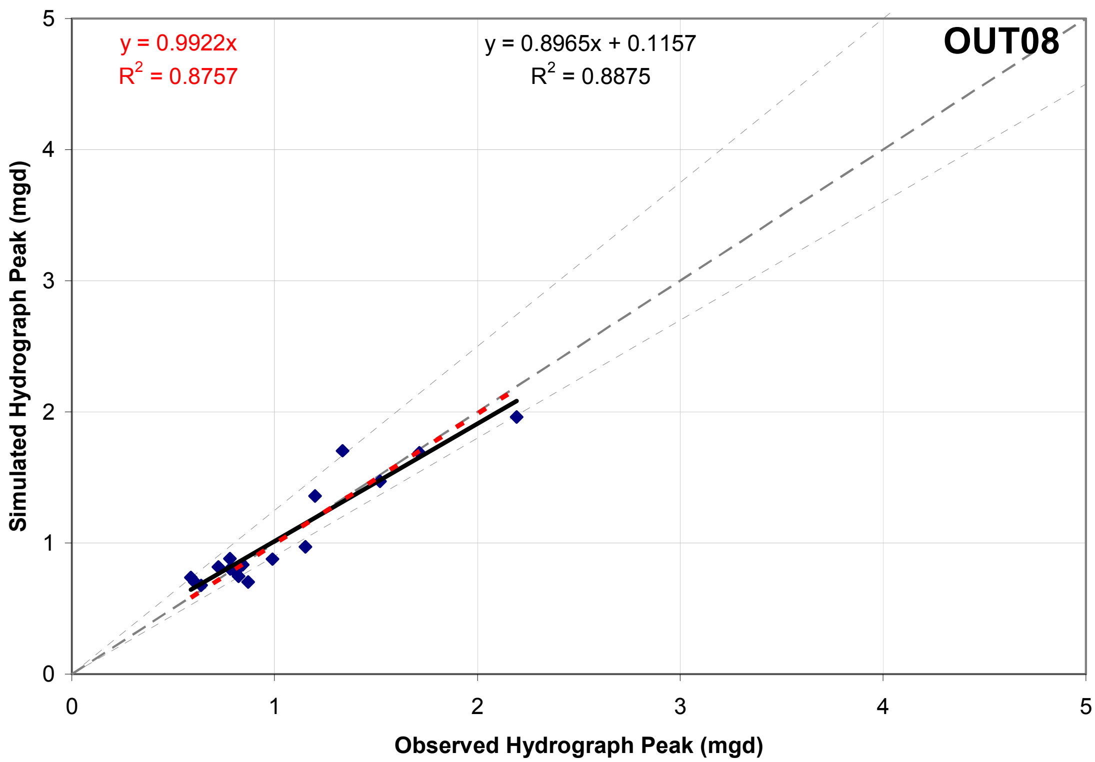
Flow Survey Location (Obs.) OUT08, Model Location (Pred.) D/S S49AA_004MH.1, Rainfall Profile: 20

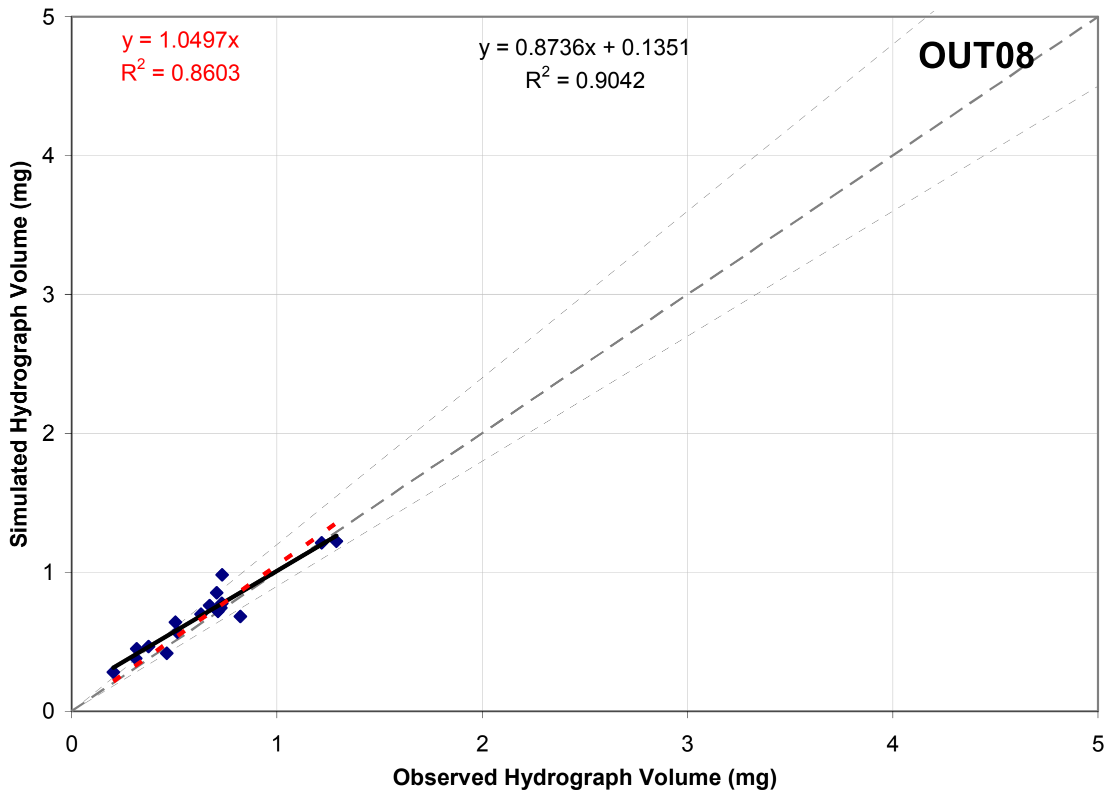


	Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
	Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain	34.755	1.434	0.004							
Obs.				0.000	6.931	0.000	2.193	178.133	0.000	2.437
...>ModelSim>A18>GaugeRain				0.282	7.026	-0.137	1.972	182.474	-0.065	3.213
...>ModelSim>A18>RadarRain				0.282	6.925	-0.239	1.710	179.548	-0.113	3.230

OUT08


y = 1.1243x
R2 = 0.8751
y = 0.969x + 8.9385
R2 = 0.918
OUT08
Crown of Pipe
Simulated Hydrograph Peak Depth (in.)
Observed Hydrograph Peak Depth (in.)
0
12
24
36
48
60
72
84
96
108

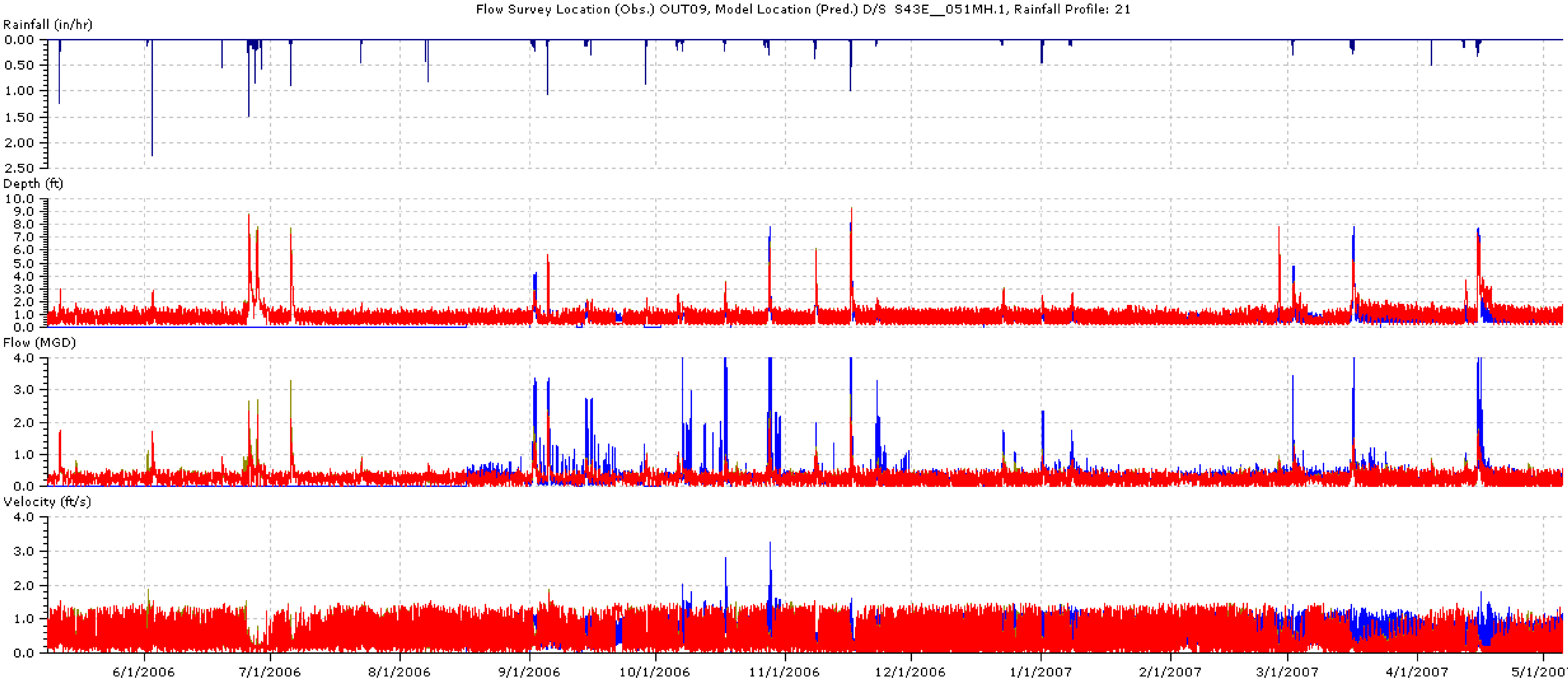

y = 0.9922x
R2 = 0.8757
y = 0.8965x + 0.1157
R2 = 0.8875
OUT08
Simulated Hydrograph Peak (mgd)
Observed Hydrograph Peak (mgd)
0
1
2
3
4
5



Notes:

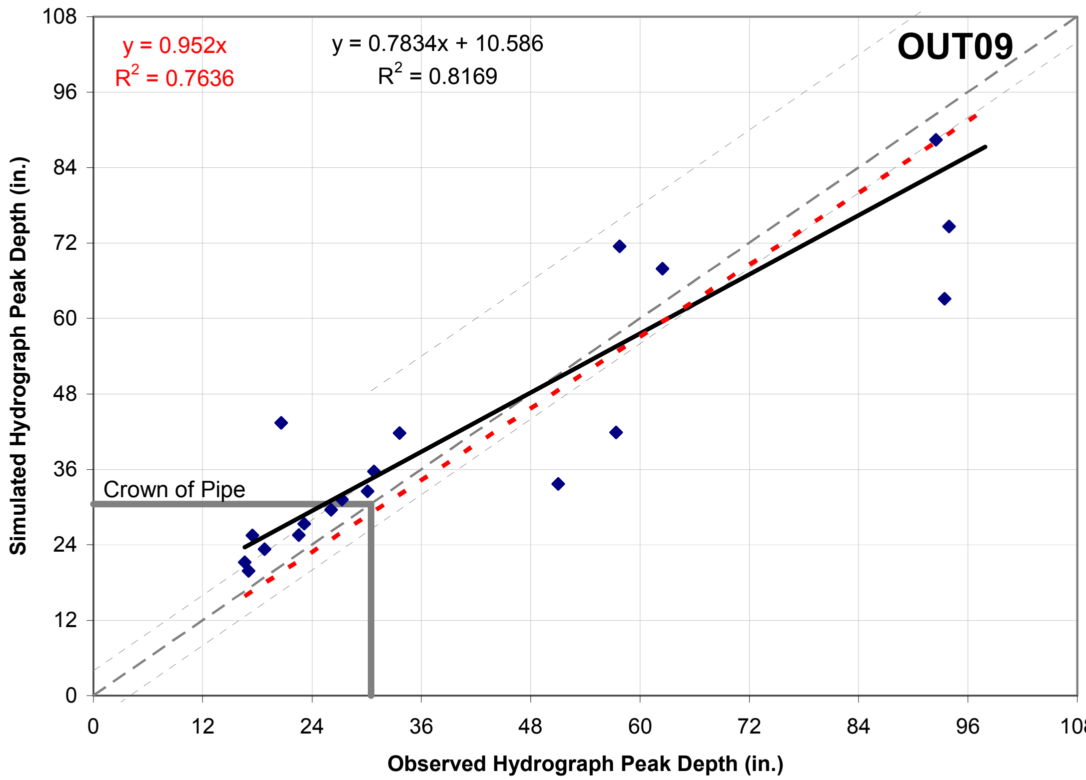
Meter OUT08 is located on a 24-inch branch sewer that connects to the Outfall Sewer. High water levels in the Outfall Sewer causes surcharging in the branch sewer at OUT08 for all of the large events and most of the smaller events.

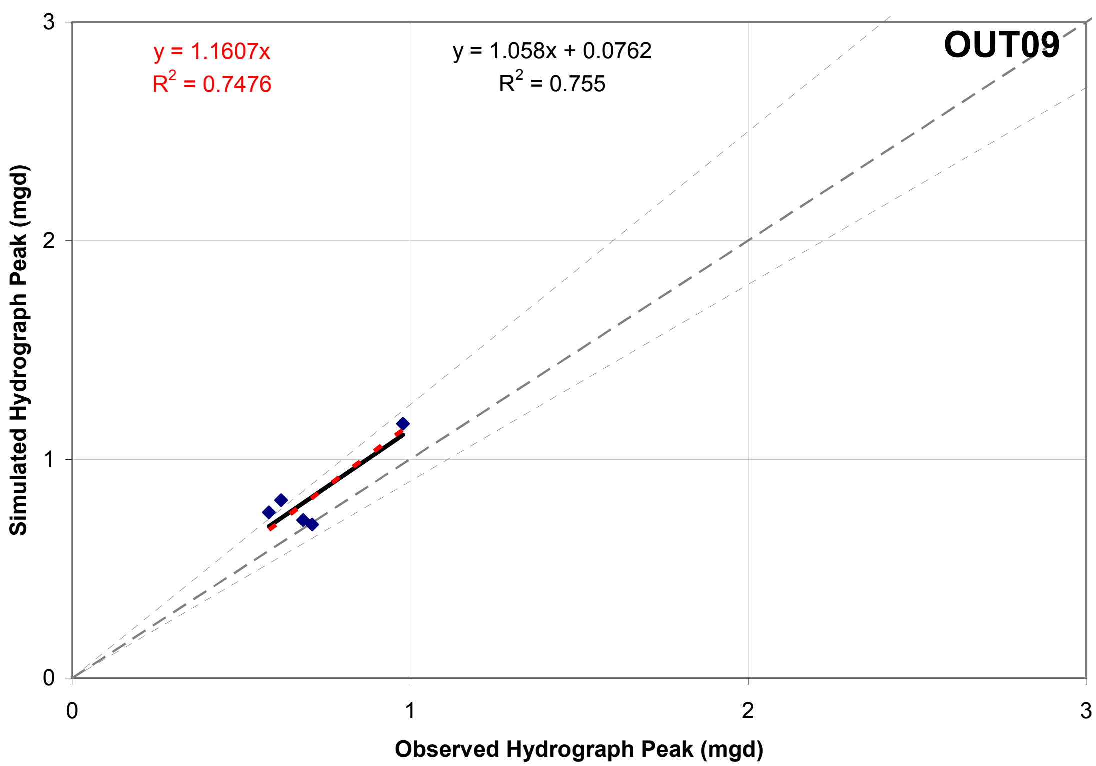
Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 18 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

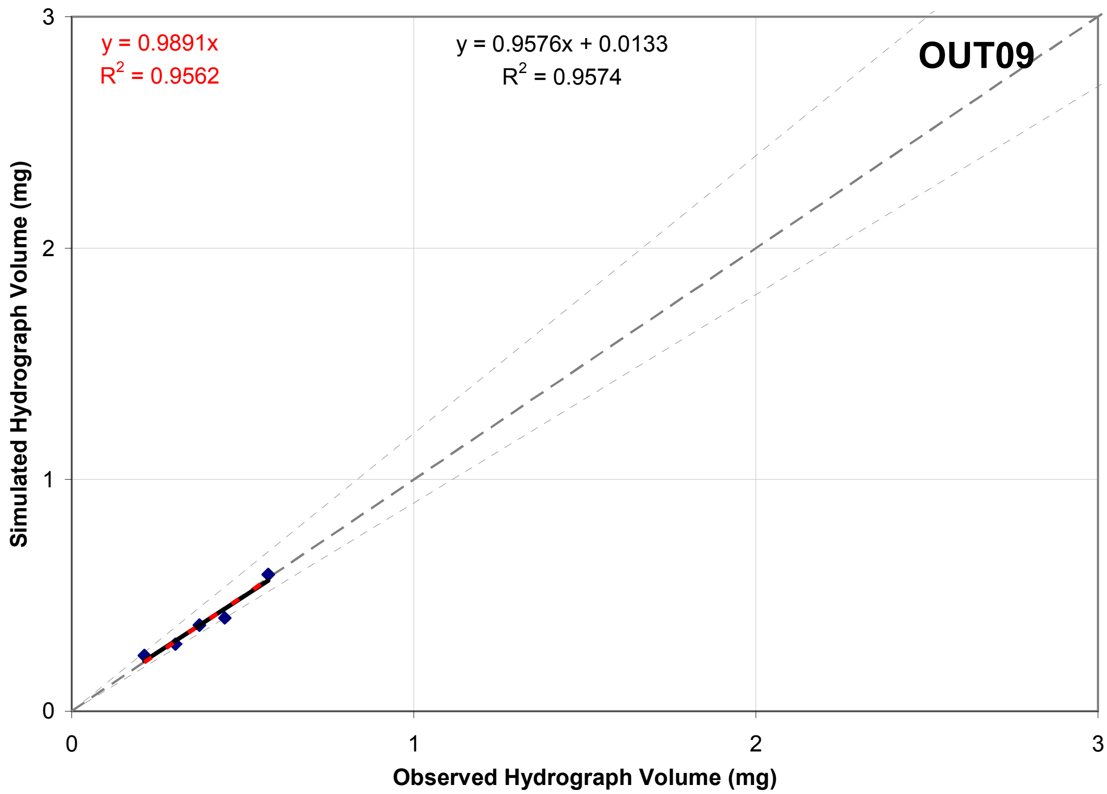


	Rainfall Depth (in)	Rainfall Peak (in/hr)	Rainfall Average (in/hr)	Depth (ft) Min	Depth (ft) Max	Flow (MGD) Min	Flow (MGD) Max	Flow (MGD) Volume (US Mgal)	Velocity (ft/s) Min	Velocity (ft/s) Max
Rain	35.945	2.248	0.004							
Obs.				0.000	8.158	0.000	10.314	90.046	0.000	3.236
...>ModelSim>A18>GaugeRain				0.214	9.288	-7.182	3.305	101.832	-1.987	1.860
...>ModelSim>A18>RadarRain				0.213	9.211	-6.999	2.339	96.803	-1.937	1.763

OUT09


y = 0.952x
R^2 = 0.7636
y = 0.7834x + 10.586
R^2 = 0.8169
OUT09
Crown of Pipe
Simulated Hydrograph Peak Depth (in.)
Observed Hydrograph Peak Depth (in.)
0
12
24
36
48
60
72
84
96
108


y = 1.1607x
R^2 = 0.7476
y = 1.058x + 0.0762
R^2 = 0.755
OUT09
Simulated Hydrograph Peak (mgd)
Observed Hydrograph Peak (mgd)
0
1
2
3



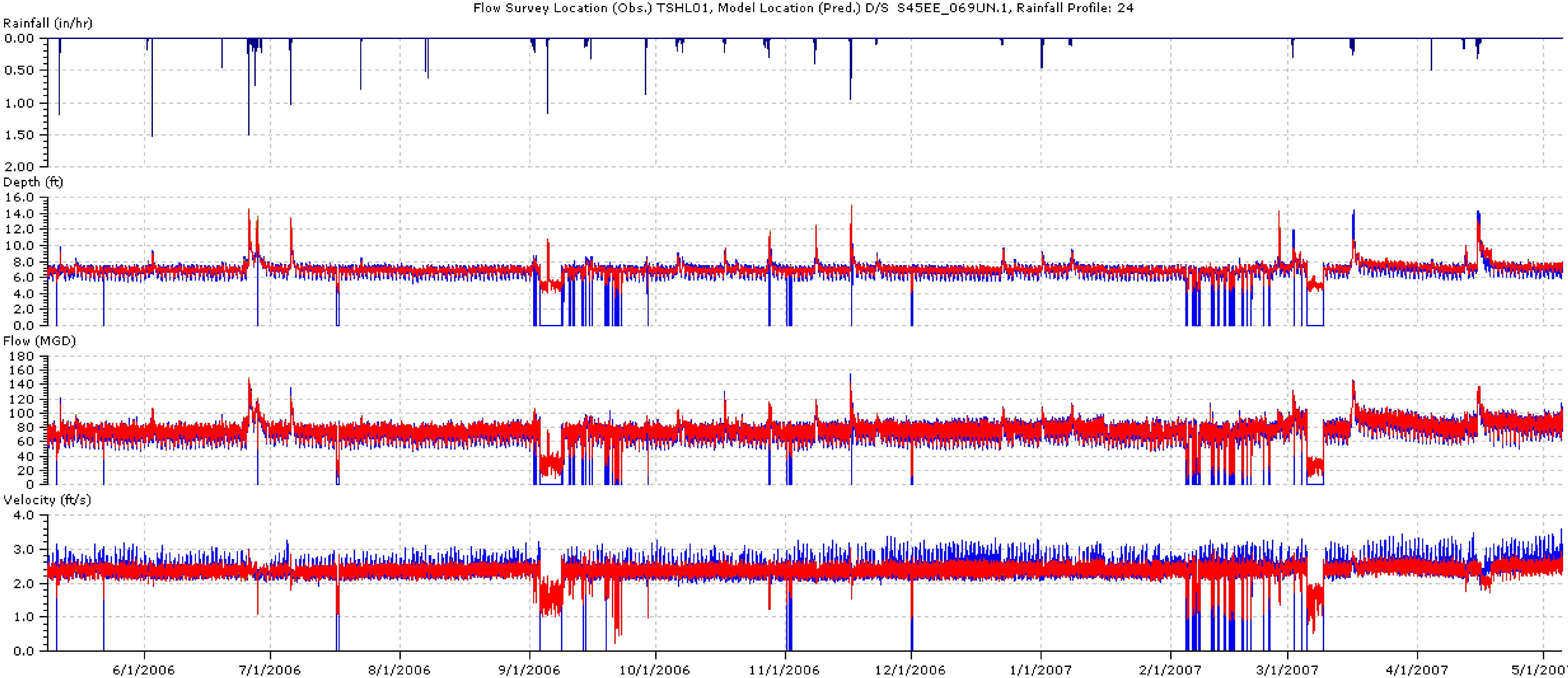
Notes:

Meter OUT09 is a FlowShark meter mounted in the branch sewer that connects to the upstream end of the 99-inch sewer. Meter OUT07 is an Isco meter on the same sewer, approximately five hundred linear feet upstream. Both OUT07 and OUT09 experience surcharging due to high water levels in the 99-inch sewer. The surcharging may be associated with episodes of reverse flow in the sewer. Peak measured flows may be associated with flow reversals and may not be an indication of peak flow generated in the meter basin area.

Measured velocities are very low (less than 1 ft/s), which is a cause for greater uncertainty in the measured flow values.

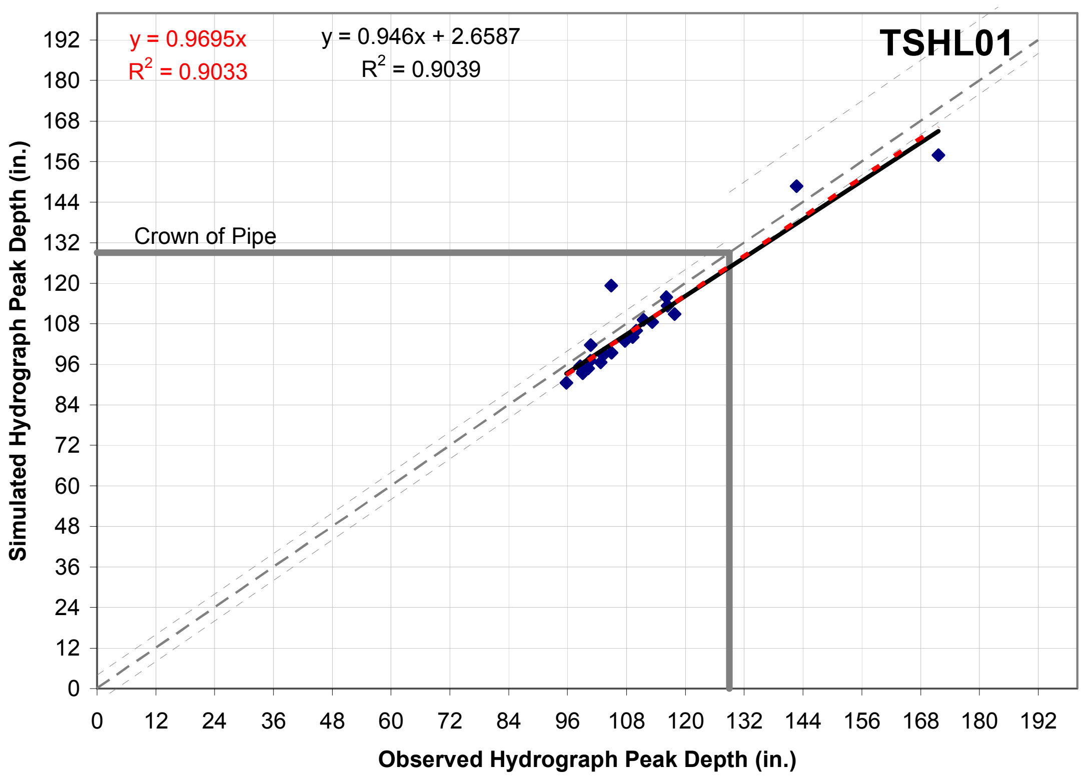
Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 20 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

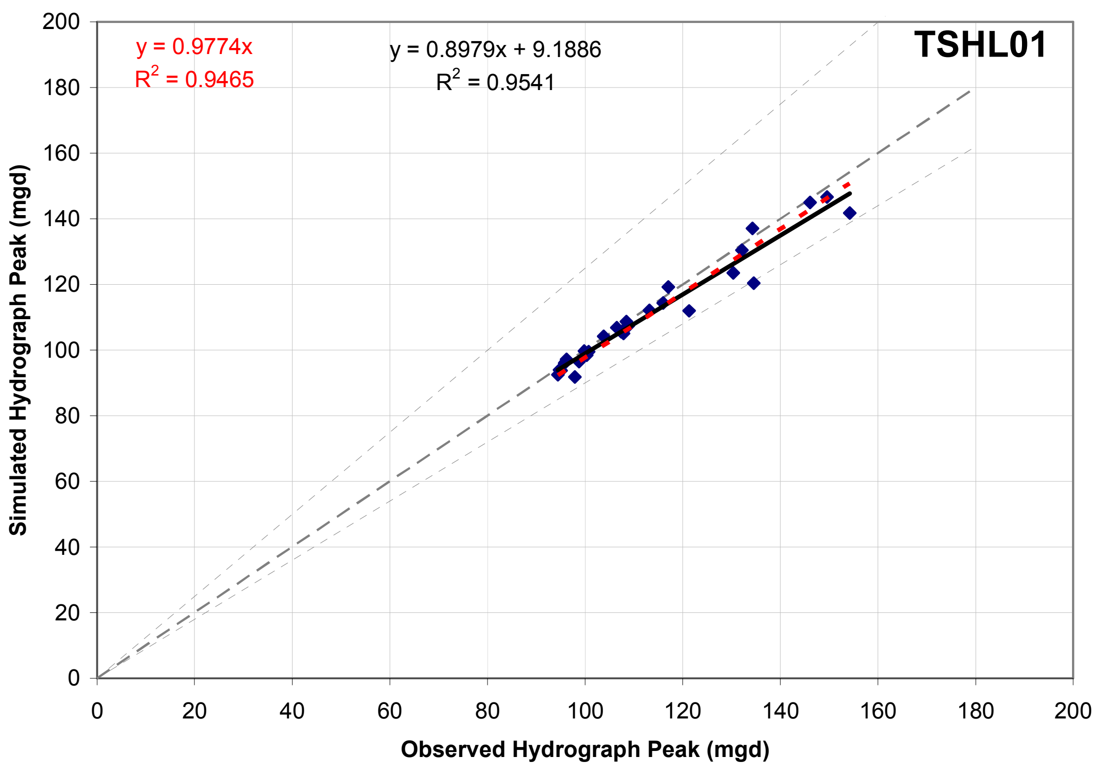
Flow Survey Location (Obs.) TSHL01, Model Location (Pred.) D/S S45EE_069UN.1, Rainfall Profile: 24

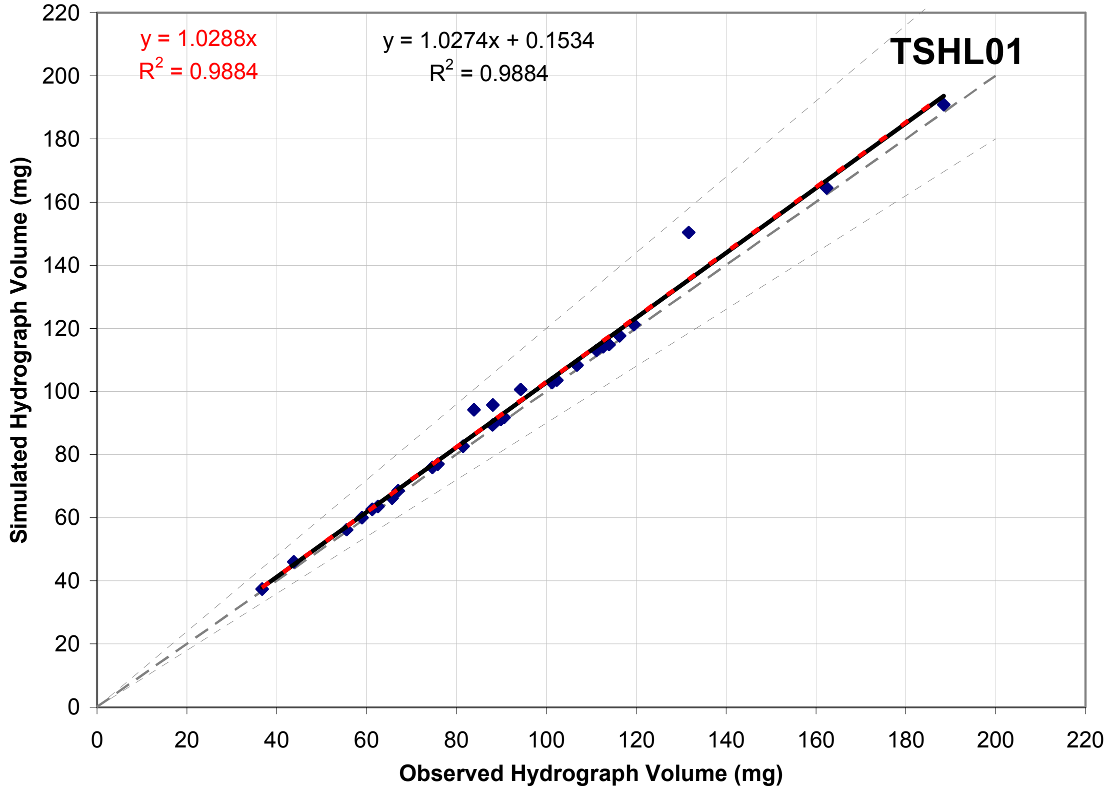


	Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
	Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain	35.466	1.528	0.004							
Obs.				0.000	14.470	0.000	154.221	26660.863	0.000	3.577
...>ModelSim>A18>GaugeRain				3.508	15.048	1.154	148.814	27469.208	0.228	3.042
...>ModelSim>A18>RadarRain				3.508	14.938	1.154	146.968	27458.743	0.228	3.041

TSHL01


y = 0.9695x
R2 = 0.9033
y = 0.946x + 2.6587
R2 = 0.9039
TSHL01
Crown of Pipe
Simulated Hydrograph Peak Depth (in.)
Observed Hydrograph Peak Depth (in.)
0
12
24
36
48
60
72
84
96
108
120
132
144
156
168
180
192


y = 0.9774x
R2 = 0.9465
y = 0.8979x + 9.1886
R2 = 0.9541
TSHL01
Simulated Hydrograph Peak (mgd)
Observed Hydrograph Peak (mgd)
0
20
40
60
80
100
120
140
160
180
200



Notes:

TSHL01 is located at the upstream end of the Outfall sewer just downstream of the connection with the 99-inch sewer. The flow at this meter is essentially the sum of the flows from the High Level/Jones Falls sewersheds and the Low Level sewershed.

In general the depth, velocity, and flow data from this FlowShark meter are consistent and reliable. There are gaps of missing data at times, most notably during the 9/5/2006 events.

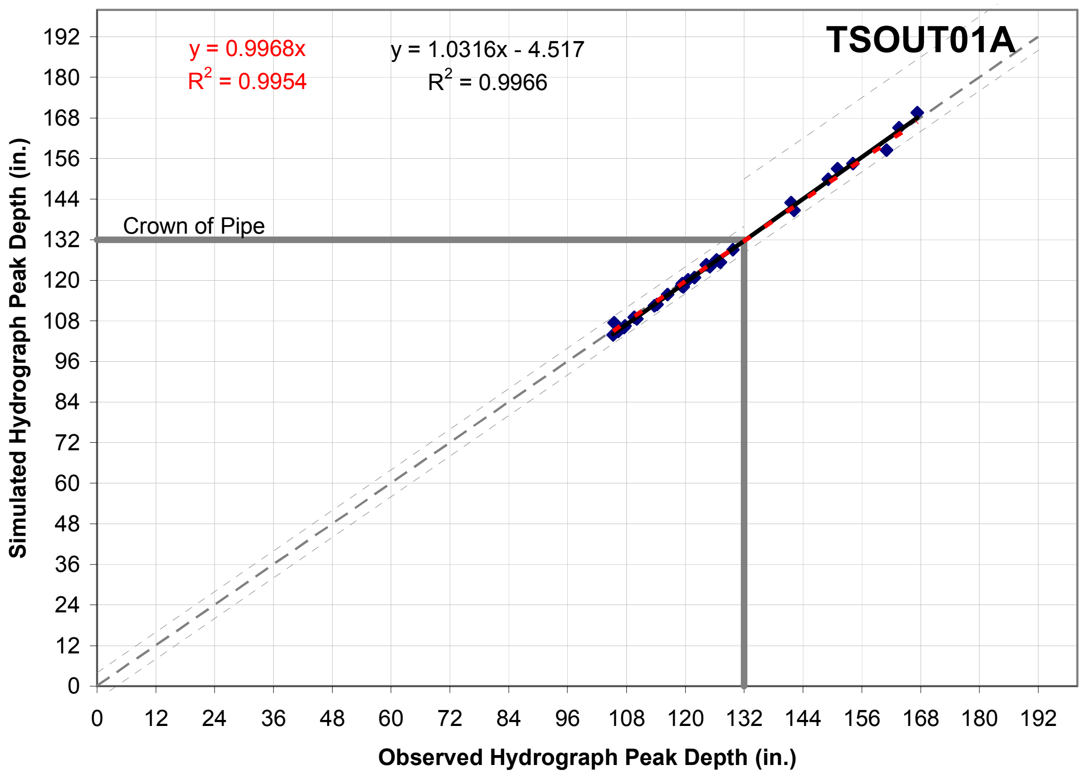
This meter data was used to create the inflow boundary conditions from the High Level/Jones Falls sewersheds. Gaps in the data cause brief irregularities in the simulations at all downstream meter sites along the Outfall sewer.

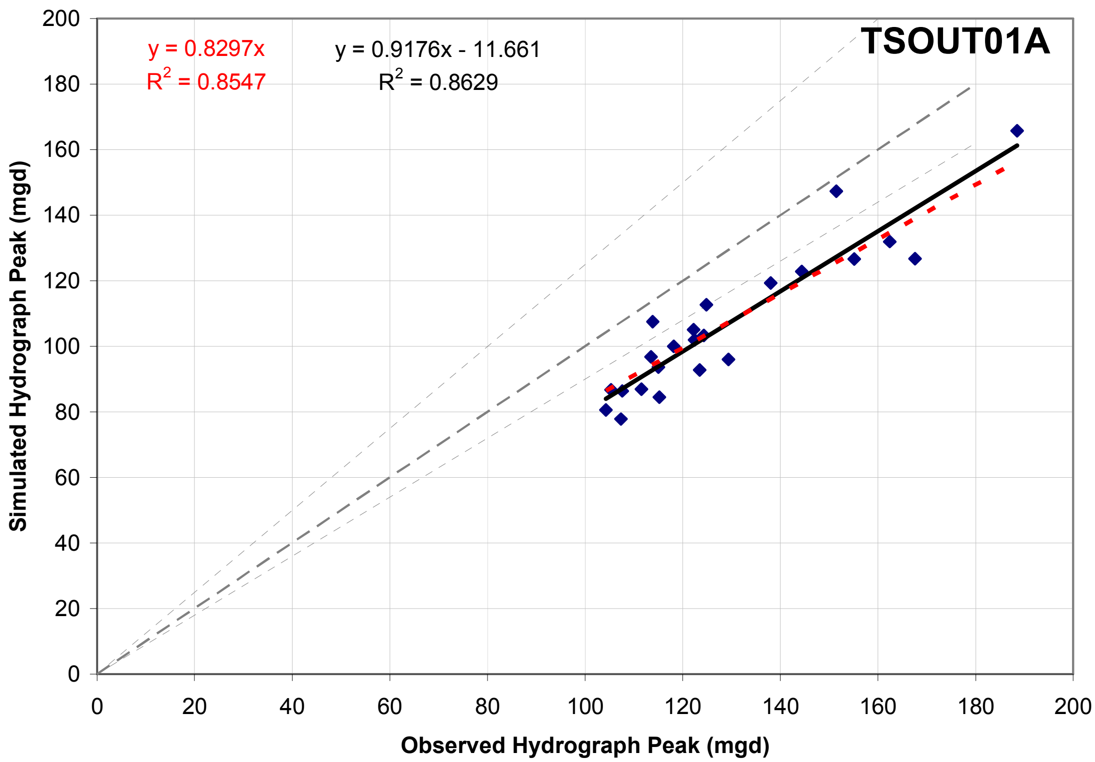
Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 21 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

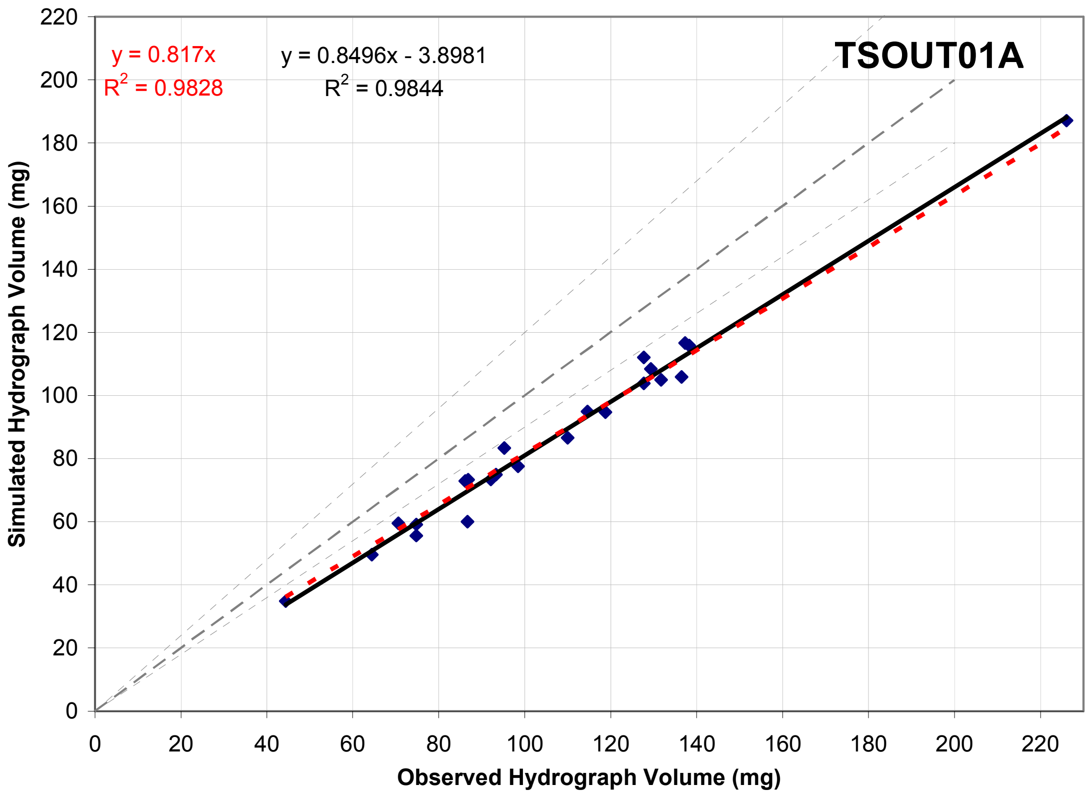
Flow Survey Location (Obs.) TSOUT01A, Model Location (Pred.) D/S S69A__004MH.1, Rainfall Profile: 25

	Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
	Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain	37.974	2.316	0.004							
Obs.				0.000	16.180	0.000	188.490	31834.090	0.000	3.182
...>ModelSim>A18>GaugeRain				5.646	16.033	-43.850	165.923	25060.918	-0.787	3.552
...>ModelSim>A18>RadarRain				5.644	16.030	-43.854	165.653	25020.734	-0.787	3.552

TSOUT01A


TSOUT01A
y = 0.9968x
R2 = 0.9954
y = 1.0316x - 4.517
R2 = 0.9966
Crown of Pipe
Simulated Hydrograph Peak Depth (in.)
Observed Hydrograph Peak Depth (in.)
0
12
24
36
48
60
72
84
96
108
120
132
144
156
168
180
192


TSOUT01A
y = 0.8297x
R2 = 0.8547
y = 0.9176x - 11.661
R2 = 0.8629
Simulated Hydrograph Peak (mgd)
Observed Hydrograph Peak (mgd)
0
20
40
60
80
100
120
140
160
180
200



Notes:

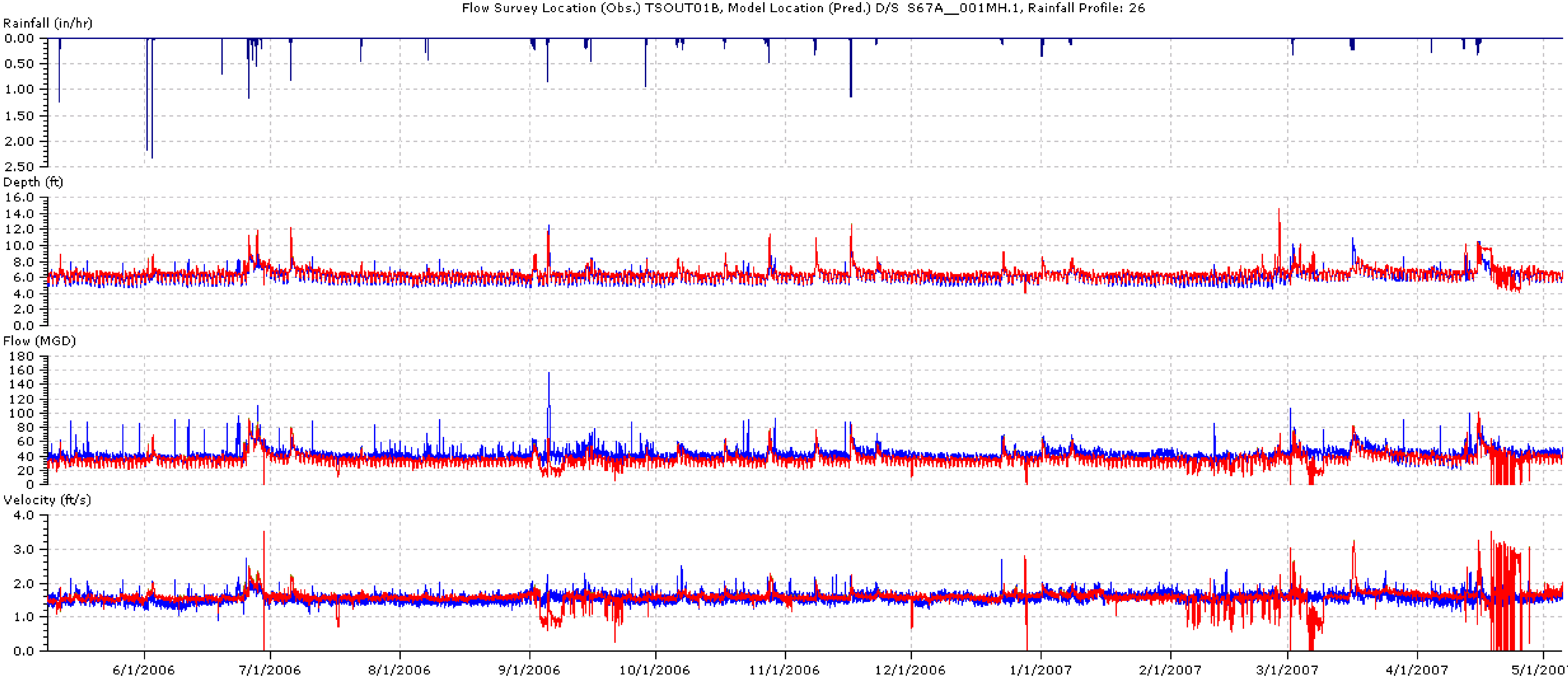
Meter TSOUT01A is located on the 132-inch Outfall sewer at the Baltimore County line. Flow is shared between the Outfall sewer and the parallel Relief sewer. The balance of flow between these two lines is very sensitive to the assumed water levels used as downstream boundary condition in the InfoWorks™ model. The calibrated model configuration results in approximately two thirds of the flow conveyed by the Outfall Sewer and one third by the Relief Sewer.

Simulated flow in the Outfall sewer at TSHL01A is typically less than measured flows. The difference may be due to several factors:

- Uncertainty in the measured flow values at TSOUT01A and TSOUT01B.
- Uncertainty in measured flows at upstream meters.
- Sensitivity to the boundary conditions that control the balance of flow between the Outfall and Relief Sewers.
- Uncertainty in the measured sediment deposits in the pipes (especially during peak flow conditions which may be different from the sediment survey conditions)

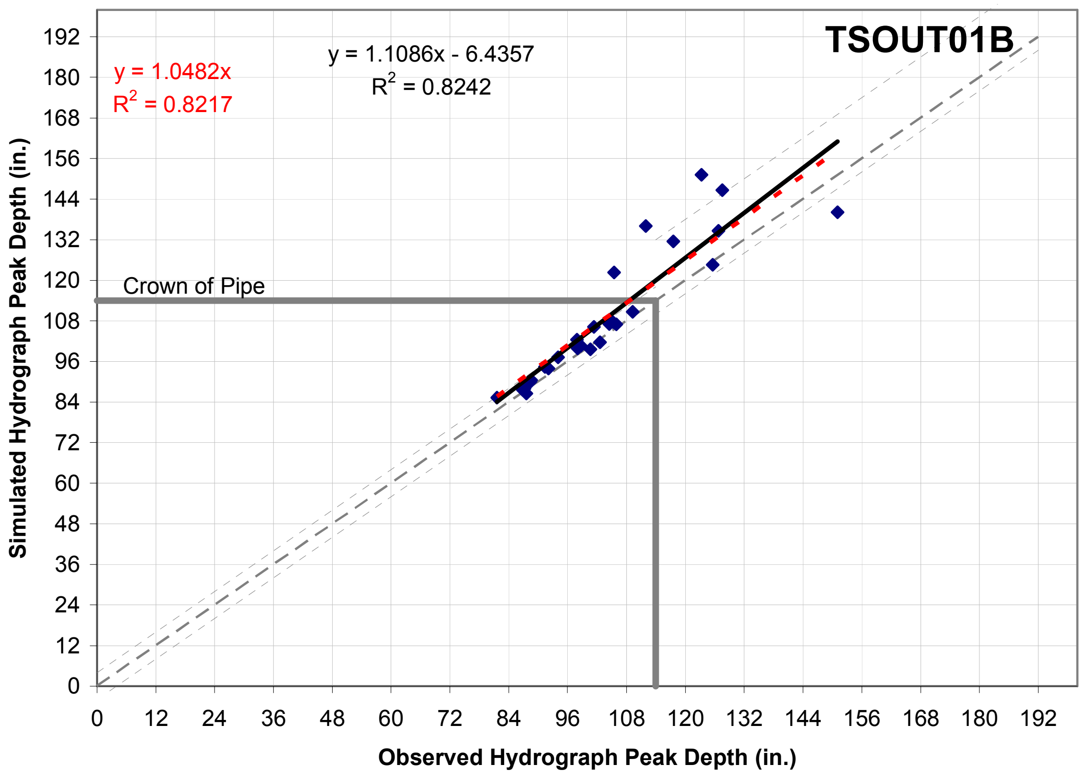
Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 22 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

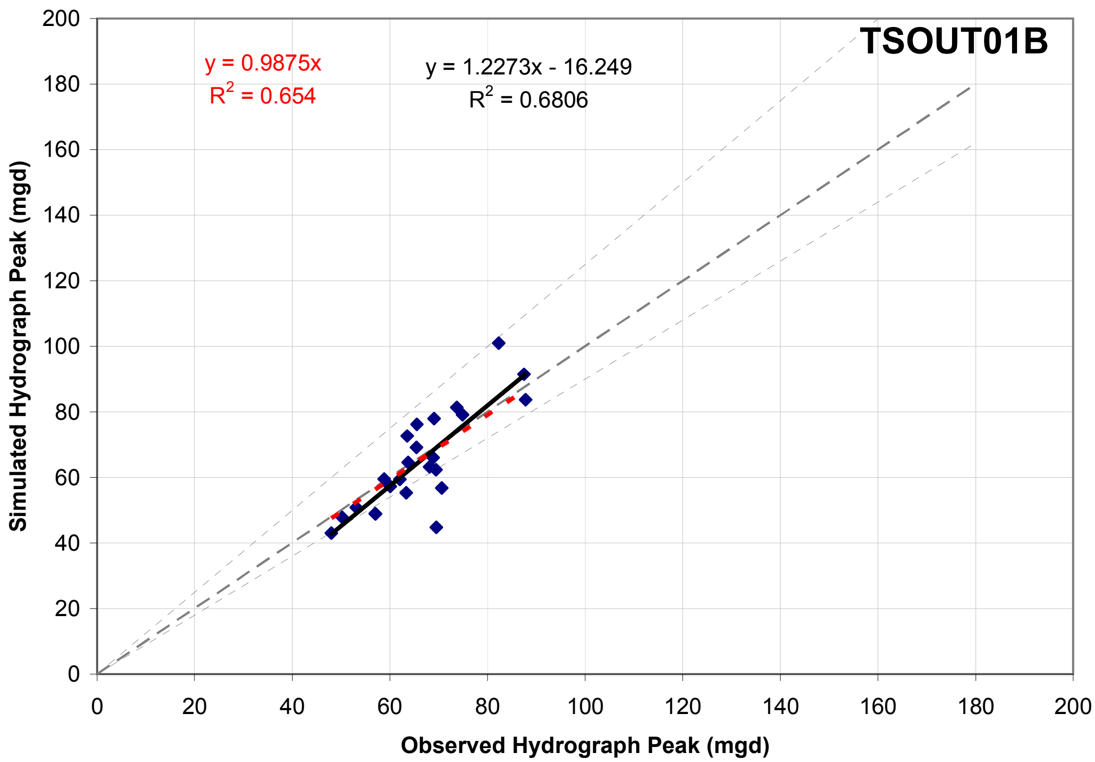
Flow Survey Location (Obs.) TSOUT01B, Model Location (Pred.) D/S S67A__001MH.1, Rainfall Profile: 26

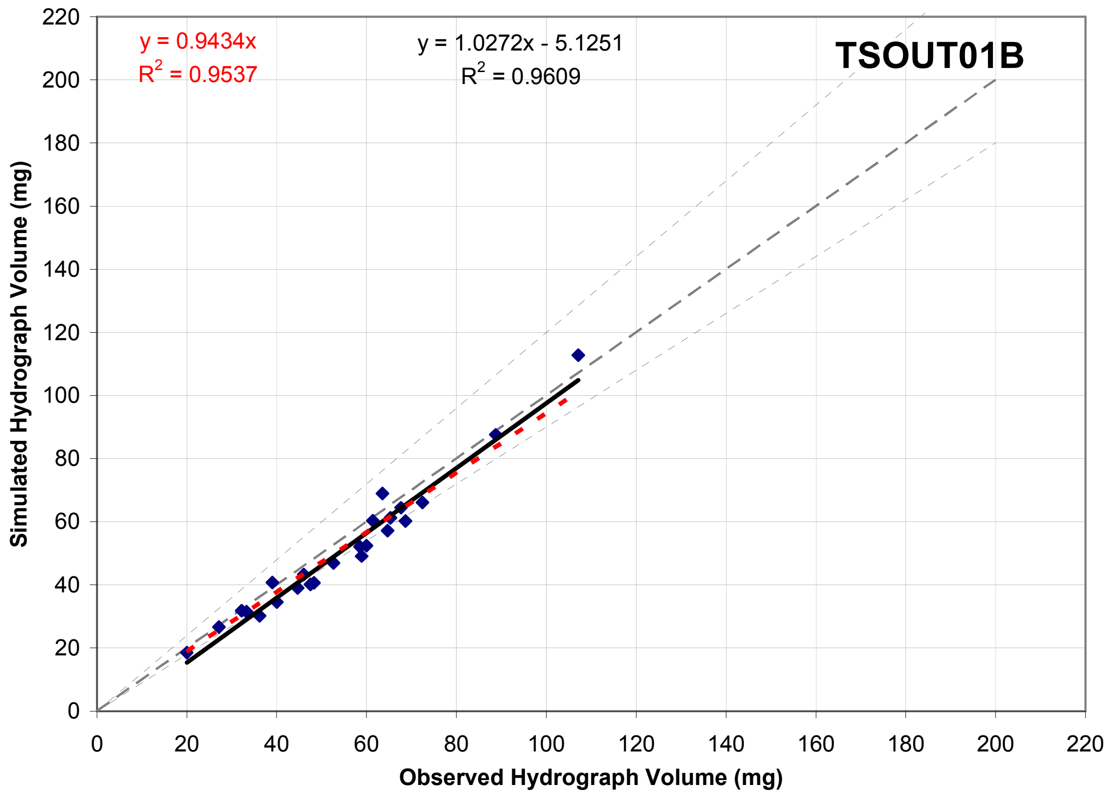


	Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
	Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain	37.974	2.316	0.004							
Obs.				4.630	12.591	21.088	156.375	14954.901	0.889	2.740
...>ModelSim>A18>GaugeRain				4.151	14.501	-39.643	101.217	12942.860	-1.459	3.531
...>ModelSim>A18>RadarRain				4.148	14.499	-39.647	101.028	12917.993	-1.459	3.531

TSOUT01B


TSOUT01B
y = 1.0482x
R2 = 0.8217
y = 1.1086x - 6.4357
R2 = 0.8242
Crown of Pipe
Simulated Hydrograph Peak Depth (in.)
Observed Hydrograph Peak Depth (in.)
0
12
24
36
48
60
72
84
96
108
120
132
144
156
168
180
192


TSOUT01B
y = 0.9875x
R2 = 0.654
y = 1.2273x - 16.249
R2 = 0.6806
Simulated Hydrograph Peak (mgd)
Observed Hydrograph Peak (mgd)
0
20
40
60
80
100
120
140
160
180
200



Notes:

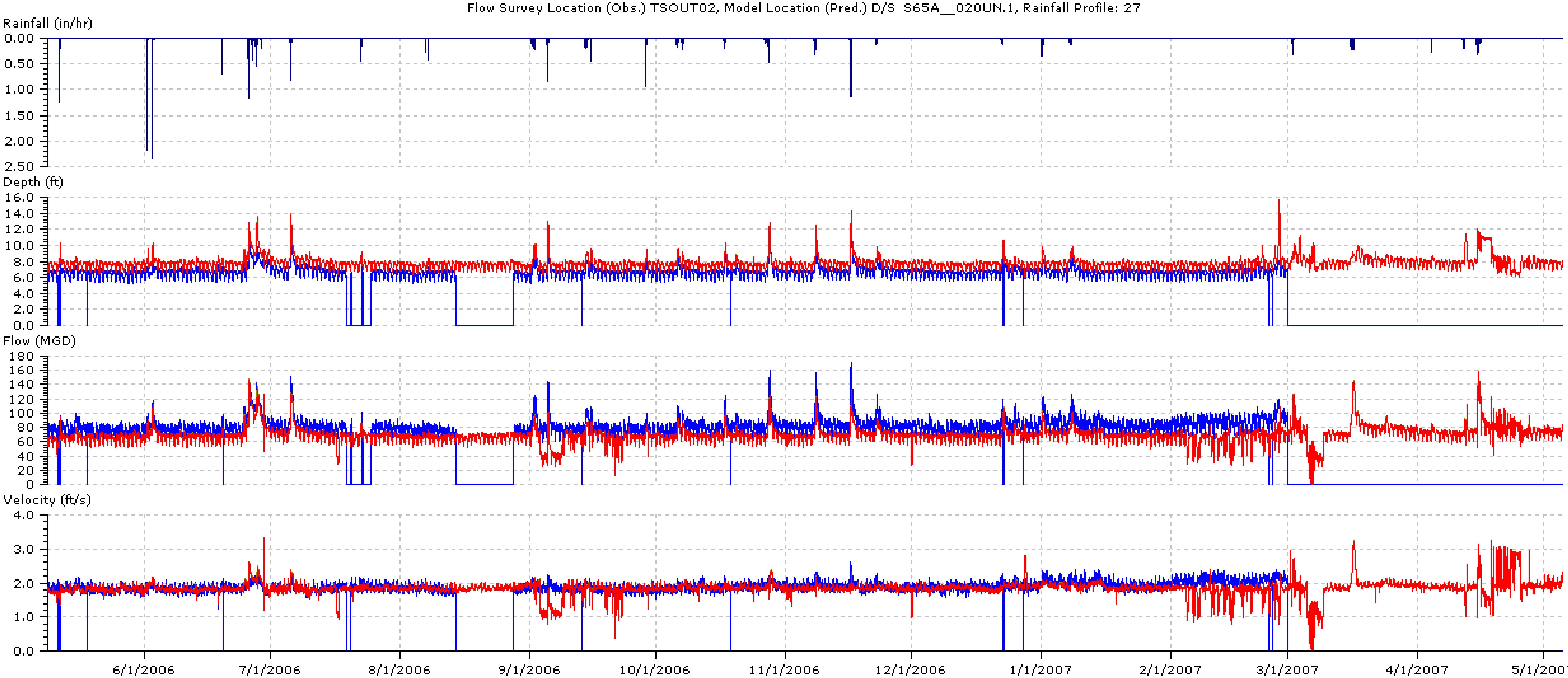
Meter TSOUT01B is located on the 114-inch Relief sewer at the Baltimore County line. Flow is shared between the Outfall Sewer and the parallel Relief Sewer. The balance of flow between these two lines is very sensitive to the assumed water levels used as downstream boundary condition in the InfoWorks™ model. The calibrated model configuration results in approximately two thirds of the flow conveyed by the Outfall Sewer and one third by the Relief Sewer.

Simulated flow in the Relief sewer at TSHL01B matches the measured flow values but this must also be viewed along side the calibration results at TSOUT01A in the Outfall sewer. The difference may be due to several factors:

- Uncertainty in the measured flow values at TSOUT01A and TSOUT01B.
- Uncertainty in measured flows at upstream meters.
- Sensitivity to the boundary conditions that control the balance of flow between the Outfall and Relief Sewers.
- Uncertainty in the measured sediment deposits in the pipes (especially during peak flow conditions which may be different from the sediment survey conditions)

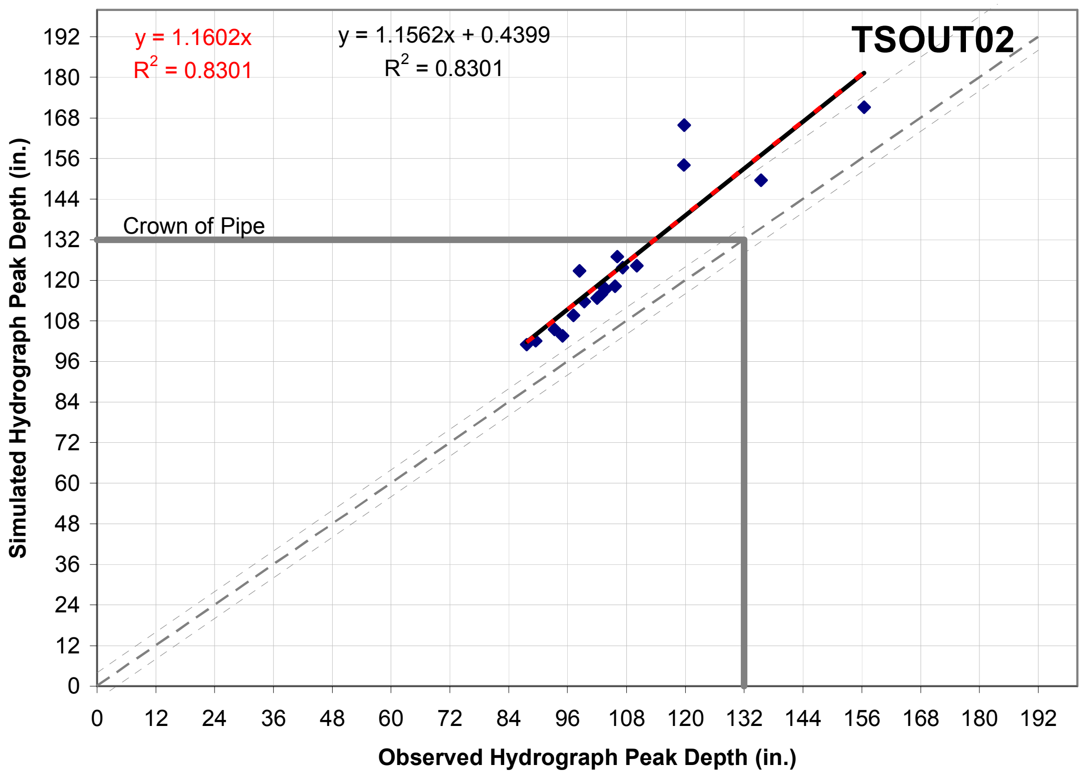
Observed / Predicted Plot Produced by dperry (2/23/2009 1:09:42 PM) Page 23 of 23
Flow Survey: >Outfall Catchment Group>Flow Survey Group>Outfall Flow Survey Measurement (2/26/2008 1:20:50 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>GaugeRain (2/20/2009 5:57:04 PM)
Sim: >Outfall Catchment Group>ModelSim>A18>RadarRain (2/20/2009 7:31:08 PM)
Graph Template: >Outfall Catchment Group>Graph Template Group>A18 MeterLocations (2/12/2009 8:56:37 AM)

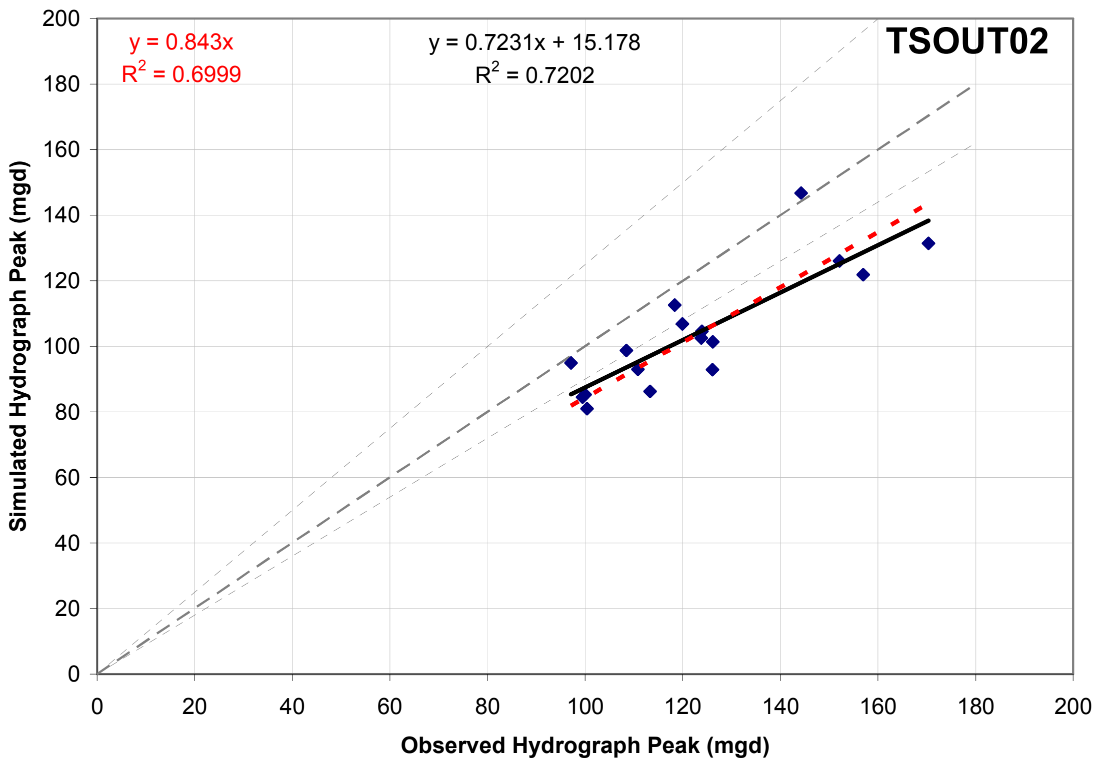
Flow Survey Location (Obs.) TSOUT02, Model Location (Pred.) D/S S65A__020UN.1, Rainfall Profile: 27

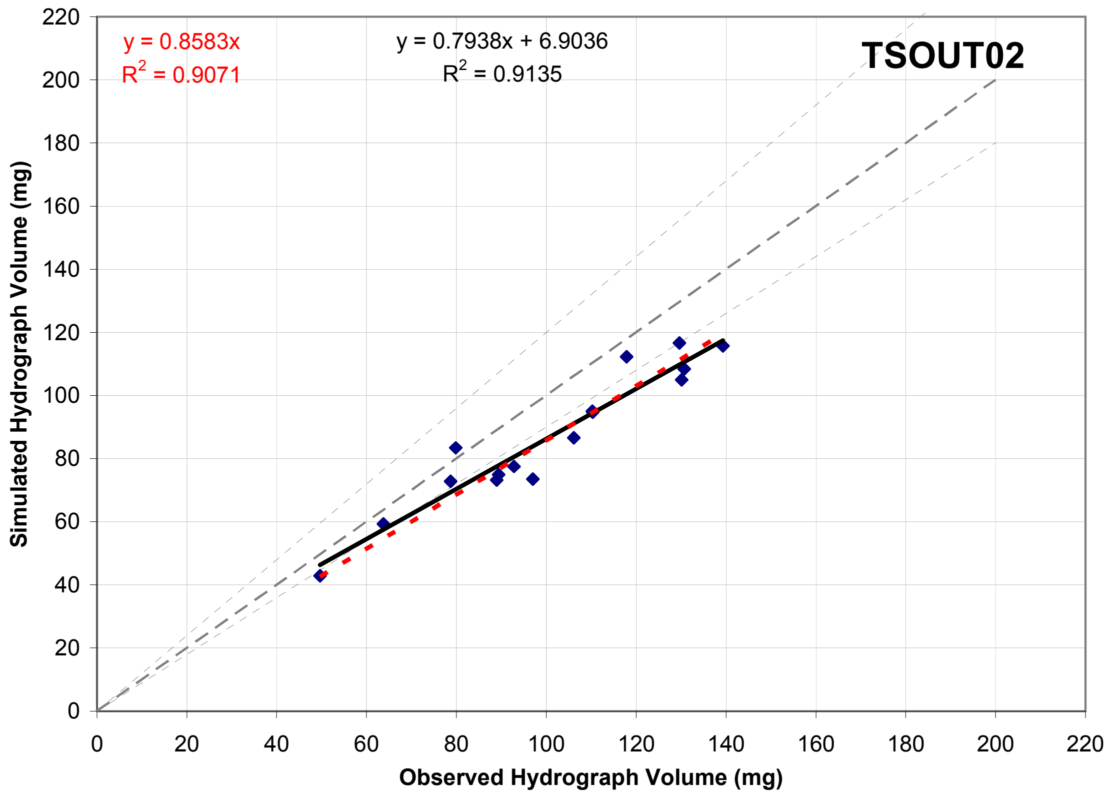


	Rainfall			Depth (ft)		Flow (MGD)			Velocity (ft/s)	
	Depth (in)	Peak (in/hr)	Average (in/hr)	Min	Max	Min	Max	Volume (US Mgal)	Min	Max
Rain	37.974	2.316	0.004							
Obs.				0.000	13.038	0.000	170.365	22494.609	0.000	2.603
...>ModelSim>A18>GaugeRain				6.027	15.733	-36.024	158.126	25076.291	-0.734	3.325
...>ModelSim>A18>RadarRain				6.024	15.728	-36.028	157.877	25038.637	-0.734	3.324

TSOUT02


y = 1.1602x
R^2 = 0.8301
y = 1.1562x + 0.4399
R^2 = 0.8301
TSOUT02
Crown of Pipe
Simulated Hydrograph Peak Depth (in.)
Observed Hydrograph Peak Depth (in.)
0
12
24
36
48
60
72
84
96
108
120
132
144
156
168
180
192


y = 0.843x
R^2 = 0.6999
y = 0.7231x + 15.178
R^2 = 0.7202
TSOUT02
Simulated Hydrograph Peak (mgd)
Observed Hydrograph Peak (mgd)
0
20
40
60
80
100
120
140
160
180
200



Notes:
Meter TSOUT02 is located on the 132-inch Outfall sewer upstream of TSOUT01A. TSOUT02 is downstream of the connection from Dundalk; therefore, the measured flow at TSOUT02 and TSOUT01A should be essentially equal.

In general, the simulated flows at TSOUT02 are less than the measured flows. This may indicate a high bias in the measured flow values at TSOUT02 (which is similar to, but not as great as the high bias suspected in the TSOUT01A values).

See the list of possible uncertainties given for TSOUT01A.